

Properties of Mg activation in thermally treated GaN:Mg films

C. F. Lin, H. C. Cheng, C. C. Chang, and G. C. Chi

Citation: [Journal of Applied Physics](#) **88**, 6515 (2000); doi: 10.1063/1.1308097

View online: <http://dx.doi.org/10.1063/1.1308097>

View Table of Contents: <http://scitation.aip.org/content/aip/journal/jap/88/11?ver=pdfcov>

Published by the [AIP Publishing](#)

Articles you may be interested in

[Investigation on the compensation effect of residual carbon impurities in low temperature grown Mg doped GaN films](#)

J. Appl. Phys. **115**, 163704 (2014); 10.1063/1.4873957

[Effects of KrF \(248 nm\) excimer laser irradiation on electrical and optical properties of GaN:Mg](#)

J. Vac. Sci. Technol. B **21**, 641 (2003); 10.1116/1.1545732

[Electrical and optical properties of beryllium-implanted Mg-doped GaN](#)

J. Appl. Phys. **92**, 1881 (2002); 10.1063/1.1494110

[Strong acceptor density and temperature dependences of thermal activation energy of acceptors in a Mg-doped GaN epilayer grown by metalorganic chemical-vapor deposition](#)

Appl. Phys. Lett. **80**, 1001 (2002); 10.1063/1.1448666

[Structural defects and microstrain in GaN induced by Mg ion implantation](#)

J. Appl. Phys. **83**, 5992 (1998); 10.1063/1.367465



Re-register for Table of Content Alerts

Create a profile.



Sign up today!



Properties of Mg activation in thermally treated GaN:Mg films

C. F. Lin^{a)} and H. C. Cheng

Department of Electronics Engineering and Institute of Electronics and Semiconductor Research Center, National Chiao Tung University, Hsinchu 30049, Taiwan, Republic of China

C. C. Chang and G. C. Chi

Department of Physics, National Central University, Chungli, Taiwan, Republic of China

(Received 5 January 2000; accepted for publication 8 July 2000)

The Mg acceptors of GaN films are activated as *p*-type GaN with rapid thermal annealing (RTA) and furnace treatments. The GaN:Mg films are activated successfully by using the RTA system below 1000 °C for 1 min. After the RTA treatment, we observed a sharper linewidth and stronger emission intensities from donor to acceptor peaks in the photoluminescence spectra. By comparing the electrical properties of GaN:Mg films at optimum conditions made with RTA (800 °C) and furnace (700 °C) treatments, we find similar activated hole concentration and a higher hole mobility for GaN:Mg films with RTA treatment at 800 °C. A higher bulk resistivity caused by increasing nitrogen vacancies is found at higher temperature and longer time RTA treatments. Faster treatment times and lower temperatures for the GaN:Mg films were achieved with the RTA activation process.

© 2000 American Institute of Physics. [S0021-8979(00)04120-7]

I. INTRODUCTION

Gallium nitride is a direct wide-band gap semiconductor, which has attracted considerable interest when applied in blue, green and ultraviolet light-emitting diodes (LEDs). Pioneering efforts have created *p*-type GaN films,¹ which are one of the keys to the success of GaN-based light-emitting devices such as LEDs² and laser diodes (LDs).³ Nakamura *et al.*⁴ reported that low-resistivity *p*-type GaN films were obtained through N₂-ambient thermal annealing or low-energy electron beam irradiation (LEEBI) treatments. Sugiura *et al.* noted that low-resistivity *p*-type GaN:Mg films had been obtained through H₂-free growth without any posttreatments.⁵ And Miyachi *et al.*⁶ reported the activation process in GaN:Mg by annealing with minority carrier injection. Prior studies^{7–9} show that the Mg–H complex¹⁰ in GaN:Mg films can be activated with an activation time in excess of 5 min, and with temperatures above 1000 °C in the rapid thermal annealing (RTA) system. The high-temperature process affected the quality of the InGaN layers in the multiple quantum well (MQW) LED structures during the LED fabrication process. In this experiment, a lower temperature and a faster RTA activation process were successfully achieved to get *p*-type GaN. The activation process for Mg-doped GaN epitaxial layers varied for the two different thermal treatments: the furnace and the RTA system. The activation temperatures were changed during both treatments. The electrical and optical properties of the activated GaN:Mg epitaxial layers will be compared in the furnace and RTA annealing systems later in this work.

II. EXPERIMENTS

The GaN:Mg films were grown by metalorganic chemical vapor deposition (MOCVD) on polished optical-grade

C-face (0001) sapphire substrates. A sapphire substrate was placed on a graphite susceptor in a horizontal type reactor with a rf heater. Trimethylgallium (TMGa), ammonia (NH₃) and bis-cyclopentadienyl-magnesium (Cp₂Mg) were used as the Ga, N and Mg sources, respectively. After growing the GaN buffer layer at 525 °C, the temperature was raised to 1025 °C to grow a thin undoped GaN epitaxial layer (as the second buffer layer) and a third 2 μm Mg-doped GaN layer was also grown, at 1025 °C, for this experiment. The as-grown GaN:Mg films were activated in N₂ ambient for 30 min with varying temperatures of 600, 700, 800 and 850 °C in the furnace system. The other series of Mg-doped GaN was activated by the RTA system and the temperature was varied from 600 to 960 °C for 1 min. The electric and optical properties in both series of GaN:Mg films were measured by the Hall effect and photoluminescence (PL) measurements. A Ni/Au (150 Å/2000 Å) metal layer was used as the ohmic contact. Using the van der Pauw method in the Hall effect measurement, in each contact, ohmic properties were observed for all of the activated GaN:Mg films from the current versus voltage (*I*–*V*) curves.

III. RESULTS AND DISCUSSION

PL spectra for the GaN:Mg films were excited with a 40 mW He–Cd laser and measured at room temperature. We observed that the typical PL emission peaks at 441 nm were caused by the transitions from the shallow donors to the Mg acceptor pairs [donor–acceptor pairs (DAPs)]. Also seen from the PL spectra from furnace-treated samples were the donor bound excitons (365 nm) peaks of GaN and the acceptor bound exciton (395 nm) peak of GaN:Mg. Fabry–Pérot fringe signals were also clearly distinguished in the PL spectra, and these signals showed the mirror-like, uniform, high crystal quality of the GaN:Mg films that were used in this experiment. The DAP peaks were fixed at 441 nm even when

^{a)}Electronic mail: cfjlin@ms32.hinet.net

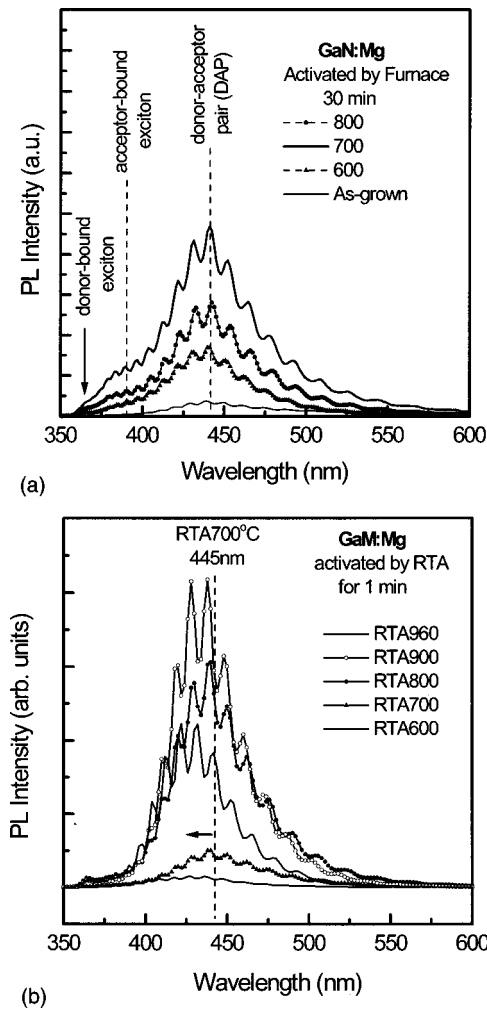


FIG. 1. PL spectra of activated Mg-doped GaN films with various activation temperatures using furnace (a) and RTA (b) systems. The Mg-related peaks in both systems are located at a wavelength of 410 nm. The typical PL peak of GaN:Mg films was due to the transition between donor and acceptor.

we varied the activation temperatures in the furnace system. From the PL spectra, we saw that for the GaN:Mg films with the RTA treatment, the wavelength of DAP peaks shifted to high energy from 446 to 430 nm by increasing the activation temperatures. The PL peak located at 430 nm was caused by a free electron–acceptor transition by the increment of ionized electrons from the donor at high activation temperatures. The transition process changed from a DAP to a free electron–acceptor transition in the PL spectra. The PL peak's movement from a DAP to acceptor bound excitons was about 104 meV. From Figs. 1(a) and 1(b), one can see that the luminescence intensity of the GaN:Mg with RTA activation was higher than that with furnace activation. The emission efficiency of GaN:Mg films with RTA activation was also higher than with furnace activation, and the emission efficiency had a stronger effect on the GaN-based optical devices. The full width of half maximum (FWHM) of the DAP transition peaks was sharper, from 56.6 to 42.6 nm, by increasing the activation temperature in the RTA system. When the activation temperature was above the optimum temperature (800 °C), the FWHM and emission intensity of the PL peak were broadened and weakened by the thermal

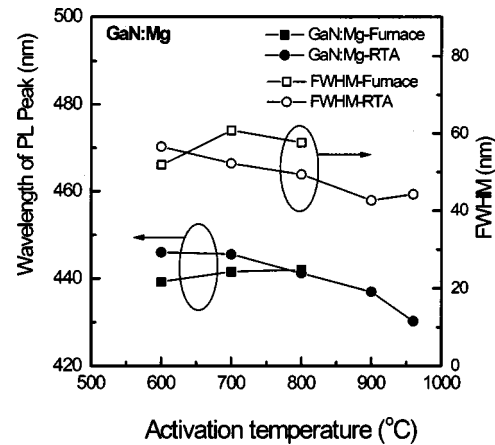


FIG. 2. Wavelength and FWHM of Mg-related PL peaks as a function of activation temperatures treated in furnace and RTA systems.

damage on the surface states of the GaN:Mg films. The peak wavelength and FWHM of the PL spectra in Fig. 2 indicate that the optimum activation temperatures are located at 700 and 800 °C in the furnace and RTA systems. The FWHM and emission intensity of the DAP peaks with the RTA (FWHM=42.6 nm) treatment are sharper and stronger than those of the GaN:Mg films in the furnace treatment (FWHM=60 nm). These sharper and stronger PL spectra with the RTA treatment have a greater effect on output power during LED operation.

To analyze the electrical properties of the Mg-doped GaN films, such as the hole mobility, the hole concentration and the bulk resistance, we used the Hall effect measurement. From Fig. 3, one can see that the maximum hole concentration of $3.6 \times 10^{17} \text{ cm}^{-3}$ and hole mobility of $9.2 \text{ cm}^2/\text{V s}$ were obtained with the furnace treatment at 700 °C annealed for 30 min. Also, the lower bulk resistivity of $1.6 \text{ } \Omega \text{ cm}$ Mg-doped GaN with 700 °C furnace treatment is shown in Fig. 4. For the RTA activation process, the hole concentration increased and the hole mobility reduced by increasing the activation temperatures from 600 to 900 °C.

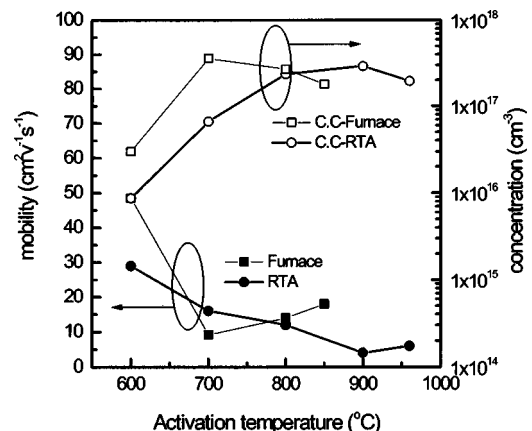


FIG. 3. Hole mobility and hole carrier concentration of activated GaN:Mg films shown as a function of activation temperatures. The active acceptor concentration increased with the activation temperature and slightly decreased over the optimum activation temperature in both the furnace and RTA systems.

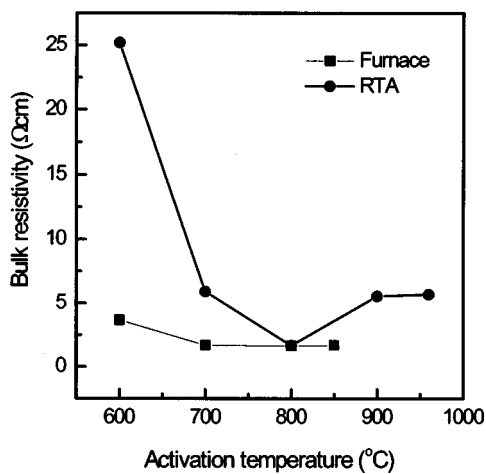


FIG. 4. Bulk resistivity of RTA and furnace treated GaN:Mg films as a function of RTA treatment temperatures. The bulk resistivity of GaN:Mg films is about 1–2 Ω cm higher than 700 °C with furnace treatment. The bulk resistivity had a stronger fluctuation with RTA treatment.

For good device performance, the *p*-type GaN must have a high hole concentration, a high mobility and a lower bulk resistance. From the data we saw that the optimum activation for the electric properties of the GaN:Mg films with the RTA treatment was located at 800 °C. The hole concentration, mobility and bulk resistance were $2.4 \times 10^{17} \text{ cm}^{-3}$, $12 \text{ cm}^2/\text{V s}$ and $1.6 \Omega \text{ cm}$ for this *p*-type GaN film. In the RTA activation process, the hole concentration and hole mobility were slightly decreased when the activation temperature was above the optimum. The Mg activation efficiency remained the same although we varied the activation temperature in the optimum temperature region. However, outside of this optimum region, it did change. Both the RTA and furnace activation processes have lower activation efficiencies when above the optimum annealing temperatures shown in Fig. 3. We compared the optimum electrical properties of GaN:Mg films with the RTA and furnace activation systems, and the hole concentration was similar in both, but the hole mobility was higher for the GaN:Mg films with the RTA treatment. The bulk resistance observed from the Hall effect measurement was located between 1 and 2 Ω cm with a furnace treatment above the 700 °C activation temperature, but this bulk resistance had a stronger fluctuation caused by a variation in the activation temperatures with the RTA system. The optimum bulk resistance for the GaN:Mg film was treated at 800 °C RTA annealing. However, the resistivity increased by raising the activation temperatures. The Ni/Au metal contacts on the GaN:Mg films with the RTA activation process all show ohmic properties. The surface states of GaN:Mg films were damaged under higher temperature RTA treatments, and the nitrogen vacancy increased during these same high-temperature and long annealing time treatments. The contact resistance on the surface damaged GaN:Mg films was increased by the high bulk resistance of the films. The GaN:Mg films were heavily damaged under high temperatures and long treatment times in the RTA process. The bulk resistance was similar at about 1.6 Ω cm under optimum conditions for the RTA and furnace systems, and a higher hole mobility of $12 \text{ cm}^2/\text{V s}$ was obtained from the RTA treatment

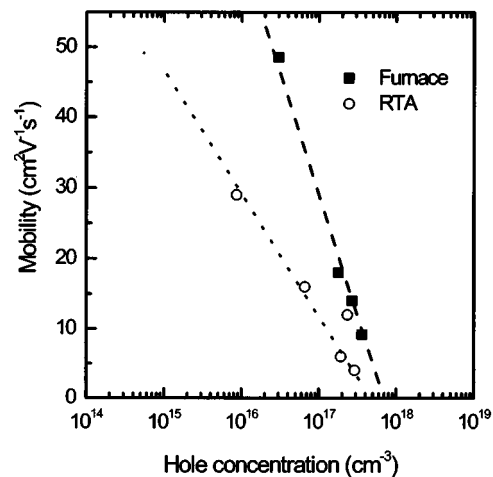


FIG. 5. Hole mobility as a function of the hole concentration varied with activation of the furnace and RTA systems.

for the *p*-type based device. The RTA activation system provided a fast, low-temperature process with better electric properties for the *p*-type GaN:Mg films.

The hole mobility as a function of the hole concentration is shown in Fig. 5. The electric properties of a series of activated GaN:Mg films in the furnace system is located at the higher slope line in Fig. 5, and the other series of GaN:Mg films activated in RTA system is located on the lower slope line. When the hole concentration increases, the mobility in both series of GaN:Mg films is decreased by the effect of ionization scattering of the hole acceptors. In this experiment, the Mg-doped GaN films obtained a similar carrier concentration and bulk resistivity and a higher hole mobility with an 800 °C RTA treatment.

IV. CONCLUSIONS

GaN:Mg films were activated by furnace and RTA systems in this experiment. The GaN:Mg films were activated in a N_2 ambient for 30 min by varying the temperatures in the furnace system. In the RTA system, the activation temperatures were varied from 600 to 960 °C for 1 min in a N_2 ambient. The FWHM and the emission intensity of the DAP peaks we saw from the PL spectra of the GaN:Mg films at room temperature with the RTA treatment were sharper and stronger than those with the furnace treatment. In the traditional furnace thermal treatment, the hole concentration and mobility were $3.6 \times 10^{17} \text{ cm}^{-3}$ and $9.2 \text{ cm}^2/\text{V s}$, respectively, with a 700 °C optimum activation temperature. The activated hole concentration was $2.4 \times 10^{17} \text{ cm}^{-3}$, the bulk resistivity was $1.6 \Omega \text{ cm}$ and the hole mobility was $12 \text{ cm}^2/\text{V s}$ with an 800 °C RTA treatment. Comparing the optimum electric properties of GaN:Mg films in the RTA (at 800 °C) and furnace (at 700 °C) activation systems, the active hole concentrations were similar and the hole mobility was higher for the GaN:Mg films with 800 °C RTA treatment. The surface states of the GaN:Mg films were damaged at high-temperature RTA treatments. When the hole concentration increased, the mobility in both series of GaN:Mg films

decreased because of the ionic acceptor scattering effect. In this experiment, the sharper and stronger PL spectra with the RTA treatment more strongly affected the output power during the homojunction blue LED operation. The result is that the RTA activation system provides a fast, low-temperature process with better electric properties for *p*-type GaN:Mg activation.

ACKNOWLEDGMENTS

This research was supported by the National Science Council of Taiwan, Republic of China, under Contract No. NSC 89-2215-E-009-069. Technical support by the Semiconductor Research Center at National Chiao Tung University is also acknowledged.

- ¹S. Nakamura, T. Mukai, M. Senoh, and N. Iwasa, *Jpn. J. Appl. Phys.*, Part 2 **31**, L139 (1992).
- ²S. Nakamura, T. Mukai, and M. Senoh, *Jpn. J. Appl. Phys.*, Part 1 **30**, 1998 (1991).
- ³S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, and Y. Sugimoto, *Jpn. J. Appl. Phys.*, Part 2 **35**, L74 (1996).
- ⁴S. Nakamura, N. Iwasa, M. Senoh, and T. Mukai, *Jpn. J. Appl. Phys.*, Part 1 **31**, 1258 (1992).
- ⁵L. Sugiura, M. Suzuki, and J. Nishio, *Appl. Phys. Lett.* **72**, 1748 (1998).
- ⁶M. Miyachi, T. Tanaka, Y. Kimura, and H. Ota, *Appl. Phys. Lett.* **72**, 1101 (1998).
- ⁷C. J. Eiting, P. A. Grudowski, J. Park, D. J. H. Lambert, B. S. Shelton, and R. D. Dupuis, *J. Electrochem. Soc.* **144**, L219 (1997).
- ⁸W. Götz, N. M. Johnson, J. Walker, D. P. Bour, and R. A. Street, *Appl. Phys. Lett.* **68**, 667 (1996).
- ⁹C. W. Wang, J. Y. Liao, C. L. Chen, and W. K. Lin, *J. Vac. Sci. Technol. B* **17**, 1545 (1999).
- ¹⁰W. Götz, N. M. Johnson, J. Walker, D. P. Bour, H. Amano, and I. Akasaki, *Appl. Phys. Lett.* **67**, 2666 (1995).