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Investigation of GaN LED with Be-implanted Mg-doped GaN layer

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Abstract

We report the electrical and optical characteristics of GaN light emitting diode (LED) with beryllium (Be) implanted Mg-doped GaN layer. The p-type layer of Be-implanted GaN LED showed a higher hole carrier concentration of 2.3×10^{18} cm^{-3} and low specific contact resistance value of 2.0×10^{-4} Ωcm^2 than as-grown p-GaN LED samples without Be-implantation. The Be-implanted GaN LEDs with InGaN/GaN MQW show slightly lower light output (about 10%) than the as-grown GaN LEDs, caused by the high RTA temperature annealing process.

Keywords: Gallium nitride (GaN); Light emitting diode (LED)

The Gallium nitride (GaN)-based semiconductors have been successfully employed to realize blue laser diodes and light-emitting diodes (LED) [1–5]. In order to fabricate these devices, it is necessary to implement controllable doping of GaN to realize both n-type and p-type GaN. Generally, n-type GaN has been achieved with the doping of Si [6] and p-type GaN is typically achieved by doping magnesium (Mg) in metal-organic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE). However, the performance of such LEDs and lasers remains limited by several problems related to the high resistance ohmic contact to the p-type GaN. Most of the reported methods for reducing p-contact resistance rely on the optimization of the contact annealing temperature and improvement of metal-semiconductor interface [7–9] and have shown improvement in the LEDs performance [10–12]. Beryllium (Be) was considered as a promising candidate for p-type doping in GaN because of its lower activation energy [13]. We adopt the ion implantation procedure for doping Be into GaN, because it can provide precise control of dopant concentration and depth distribution. A number of studies on the Be implantation of p-GaN film have been reported earlier [14–16]. Previously we reported the result of obtaining high carrier concentration and low specific resistance ohmic contact based on Be-implanted p-GaN [17–19]. But, so far no reports of the implementation of Be-implanted p-GaN film on LED structure. In this paper, we report the first experimental results including the optical, electrical properties of Be implantation in GaN LED structure and comparison with the non-implanted GaN LED. The Be implanted GaN LED shows improvement in the electrical property performance.

The GaN LED was grown by metal-organic chemical vapor deposition (MOCVD) on a *c*-axis sapphire substrate. The LED structure consists of a 30-nm-thick GaN low temperature buffer layer, a 2.0-μm-thick undoped GaN layer, a 1.5-μm-thick highly conductive n-type GaN layer, a multiple quantum wells (MQW) region consisting of five

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period 2/5-nm-thick InGaN/GaN multiple quantum wells, and a 1-μm-thick p-type GaN. For the implantation of Be ions, 1-μm-thick p-type GaN layer is necessary [17–20]. Trimethlygallium, ammonia, and CP_2Mg were used as Ga, N and Mg source, respectively. The LEDs were then implanted with Be ions at a energy of 50 keV and dose of about 10^{13} cm^{-2}. The ion projection ranges in p-type layer for energy 50 keV was estimated to be about 0.25 μm by the TRansport of Ions in Matter (TRIM) stimulation [19,20]. These implanted LEDs were subsequently rapidly thermal annealed (RTA) at 1100 °C in N_2 ambient for various periods of 15, 30 and 45 s, to repair the implantation-induced damages. The LEDs were fabricated using the standard GaN LED fabrication process [21] including lithography patterning, inductively coupled plasma reactive-ion-etching dry etching and electrode deposition, For comparison LED samples without Be-implantation were also fabricated.

The photoluminescence (PL) of p-type layer with and without Be-implantation on LEDs was investigated at room temperature using a 325 nm He–Cd laser as the excitation source. Fig. 1 shows the room temperature PL spectra of p-type layer on as-grown, as-implanted and annealed LEDs. The intensity of the PL line becomes much weaker after the implantation, indicating the occurrence of lattice damages due to the implantation. It can be seen that the annealed LEDs show a much stronger blue emission at about 440 nm corresponding to the donor-acceptor pair transition of p-GaN [18–20]. In particular the blue emission of the samples annealed for 30 s has the strongest intensity than that of others conditions. This suggests that the implantation-induced damages could be repaired, at least in part, by the RTA process for 30 s at 1100 °C.

To investigate the effect of Be-implantation on the electrical characteristics of the p-GaN layer, both the as-grown and Be-implanted LED samples were deposited with the same metallization of Ni (20 nm)/Au (100 nm) by electron beam evaporation under a pressure of 2×10^{-6} Torr and RTA 1100 °C annealed for 30 s. The measured hole carrier concentration of Be-implanted samples is 2.3×10^{18} cm^{-3} (hole mobility is 4.4 cm^2/V s) which is nearly five times higher than the as-grown sample of 5.0×10^{17} cm^{-3} (hole mobility is 10.2 cm^2/V s). Fig. 2(a) shows the *I*–*V* characteristics of the Be-implanted GaN LED samples and the as-grown GaN LEDs measured by Circular Transmission Line Method (CTLM). It can be seen that Be-implanted GaN LED sample has better linearity than as-grown sample. Total resistance (*Y*) measured by CTLM has a linear relation with pad distances (*X*) as shown in Fig. 2(b). The specific contact resistance ρ_c was determined from the linear relationship equation $Y = 2R_c + \rho_s/2\pi R \times X$, and the relation between the specific resistance and the sheet resistance $\rho_c = \rho_s \times L_T{}^2$, where R_c is the contact resistance, ρ_s the sheet resistance, and L_T is the transfer length. By fitting the data we obtain a lower specific contact resistance value of 2.0×10^{-4} Ωcm^2 for the Be-implanted samples than as-grown samples of 7.0×10^{-3} Ωcm^2. The results indicated that Be-implantation not only enhances the carrier concentration but also facilitates the p-type contact resulting in low specific resistance ohmic contact which is most desirable for optoelectronic devices. The higher carrier concentration of Be-implanted p-GaN could be responsible for the low resistance as earlier reported [19–20].

The Fig. 3(a) shows the room temperature electroluminescence (EL) spectra of the Be-implanted LED and the as-grown LED without implantation. The peak wavelength of the Be-implanted LEDs is around 430–470 nm which is slightly blue-shifted by 20 nm from that of the as-grown LED. The slight blue-shift might be also due to the change in

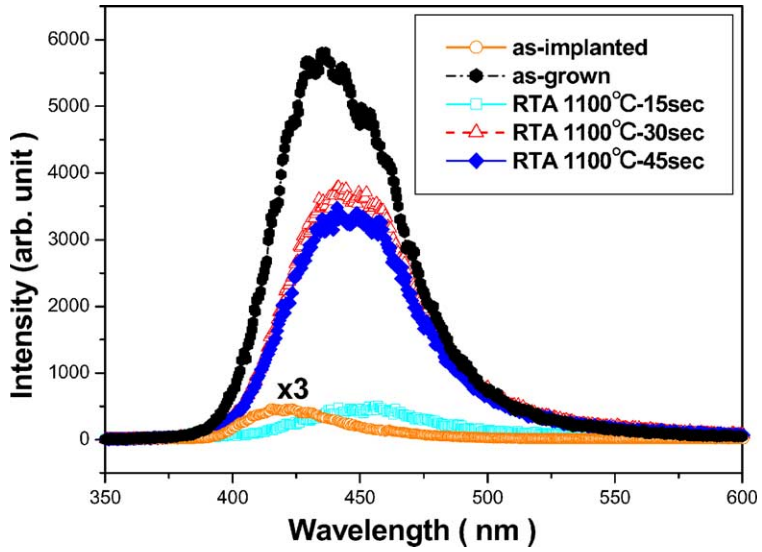

Fig. 1. PL spectra of the as-grown, as-implanted and Be-implanted Mg-doped GaN LED sample with post-annealing at annealing temperature of 1100 °C for various annealing periods.

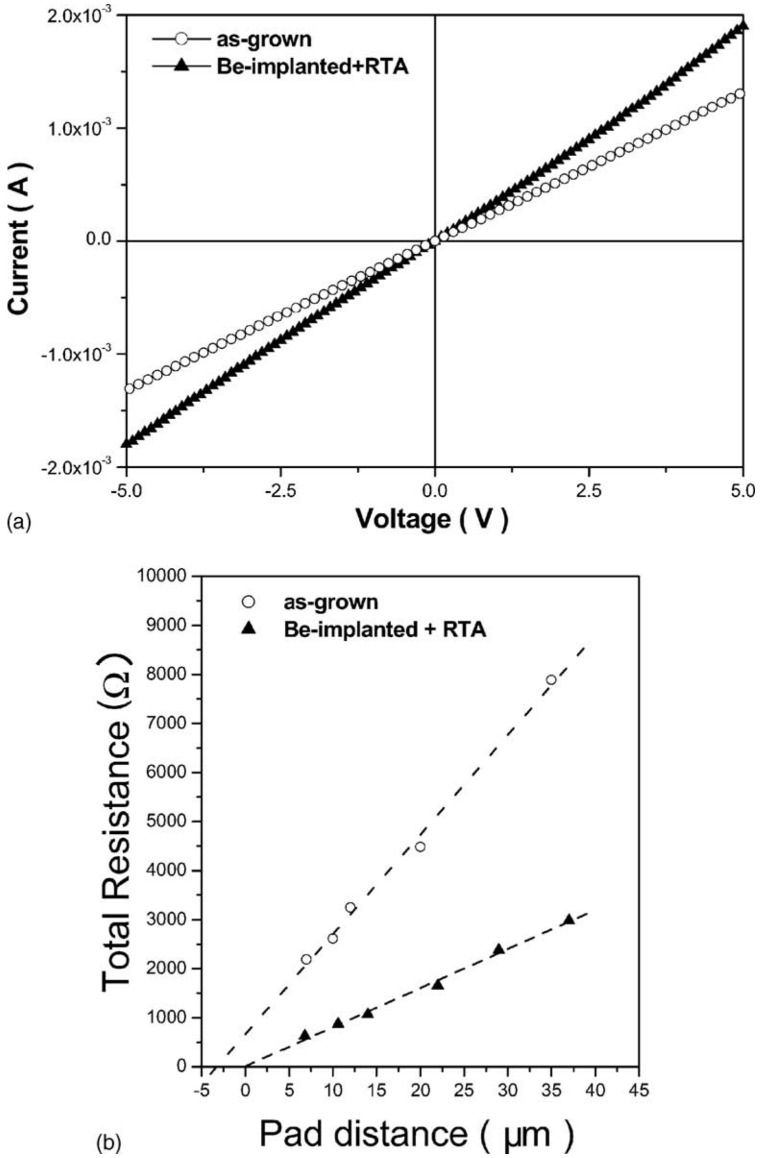

Fig. 2. (a) The *I–V* curves of Ni/Au contacts on carrier concentration of as-grown and Be-implanted Mg-doped GaN LEDs. (b) CTLM fit results of the Ni/Au on carrier concentration of as-grown and Be-implanted Mg-doped GaN LED sample with post-annealing at annealing temperature of 1100 °C for annealing 30 s.

the InGaN MQW. In content during the high temperature annealing [22–24]. The relative output luminous intensity as a function of injection current between 0 and 25 mA for the LEDs were shown in Fig. 3(b). The Be-implanted GaN LEDs shows slightly lower (about 10%) light output than the as-grown LED. This could be due to non-radiative defects and slight deterioration in the InGaN/GaN MQW active regions during the high temperature RTA process [22–24].

In summary, Be-implanted GaN LEDs with InGaN/GaN MQW were fabricated and investigated. The p-layer of Be-implanted GaN LED showed a higher hole carrier concentration of 2.3×10^{18} cm^{-3} and low specific contact resistance value of 2.0×10^{-4} Ω cm^2 than as-grown samples (hole concentration 5×10^{17} cm^{-3} and specific contact resistance 7.0×10^{-3} Ωcm^2). The Be-implanted GaN LEDs show slightly lower light output (about 10%) than the as-grown GaN LEDs possibly caused by the high RTA temperature process and implantation induced defects absorption.

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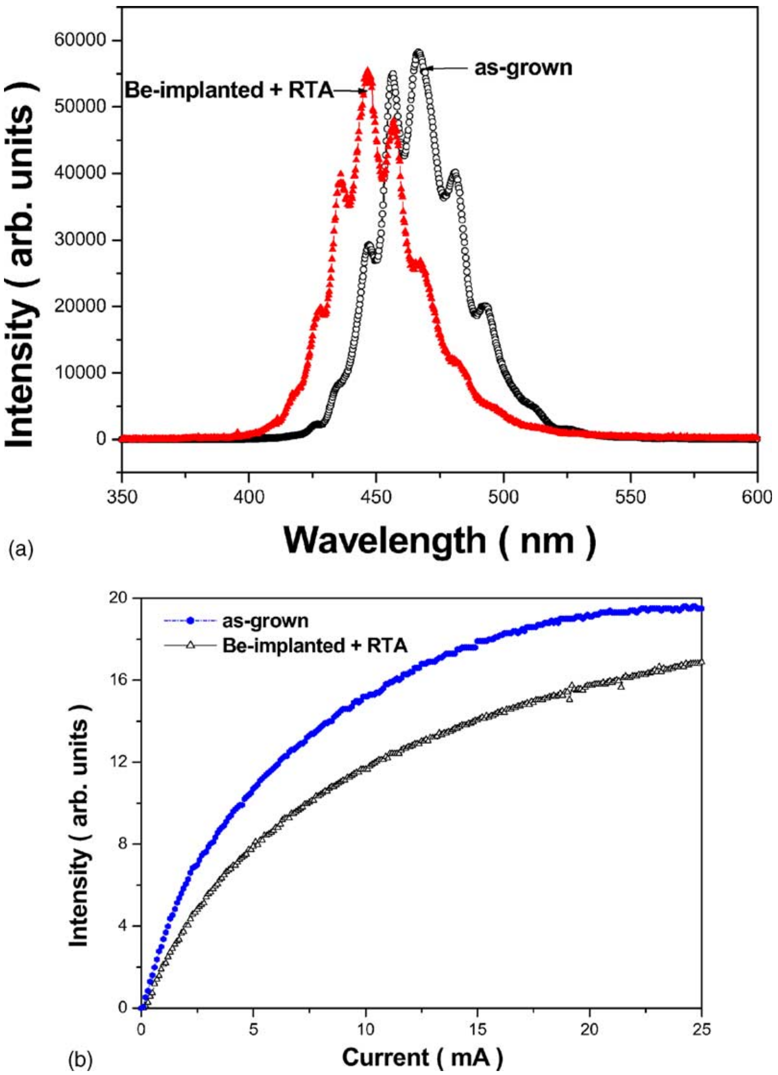

Fig. 3. (a) EL of as-grown and Be-implanted Mg doped GaN LED sample. (b) *L–I* characteristic of as-grown and Be-implanted Mg doped GaN LED sample with post-annealing at annealing temperature of 1100 °C for annealing 30 s.

References

[1] S.J. Pearton, C.B. Vartuli, J.C. Zolper, C. Yuan, R.A. Stall, Appl. Phys. Lett. 67 (1995) 1435.

[2] S. Nakamura, T. Mukai, M. Senoh, Jpn. J. Appl. Phys. 30 (Part 2) (1991) L1998.

[3] F.A. Ponce, D.P. Bour, Nature (London) 386 (1997) 351.

[4] A.G. Drizhuk, M.V. Zaitev, V.G. Sidorov, D.V. Sidorov, Tech. Phys. Lett. 22 (1996) 259.

[5] S. Nakamura, G. Fasol, The blue laser diode–gallium-nitride based light emitters and laser, Springrt, Berlin, 1997.

[6] A.V. Andrianov, D.E. Lacklison, J.W. Orton, D.J. Dewsnip, S.E. Hooper, C.T. Foxon, Semicond. Sci. Technol. 11 (1996) 366.

[7] D.J. King, L. Zhang, J.C. Ramer, S.D. Hersee, L.F. Lester, Mater. Res. Soc. Symp. Proc. 468 (1997) 421.

[8] T. Mori, T. Kozawa, T. Ohwaki, Y. Taga, S. Nagai, S. Yamasaki, S. Asami, N. Shibata, M. Koike, Appl. Phys. Lett. 69 (1996) 3537.

[9] T. Kim, J. Khim, S. Chae, T. Kim, Mater. Res. Soc. Symp. Proc. 468 (1997) 427.

[10] C.H. Kuo, S.J. Chang, Y.K. Su, L.W. Wu, J.F. Chen, J.K. Sheu, J.M. Tsai, Jpn. J. Appl. Phys. 42 (2003) 2270.

[11] C.H. Chen, S.J. Chang, Y.K. Su, Jpn. J. Appl. Phys. 42 (2003) 2281.

[12] R.C. Tu, C.J. Tun, S.M. Pan, H.P. Liu, C.E. Tsai, J.K. Sheu, C.C. Chuo, T.C. Wang, G.C. Chi, I.G. Chen, IEEE Photon. Technol. Lett. 15 (2003) 1050.

[13] F. Bernardini, V. Fiorentini, A. Bosin, Appl. Phys. Lett. 70 (1997) 2990.

[14] R.G. Willson, S.J. Pearton, C.R. Abernathy, J.M. Zavada, Appl. Phys. Lett. 66 (1995) 2238.

[15] R.G. Willson, C.B. Vartuli, S.J. Pearton, C.R. Abernathy, J.M. Zavada, Solid-State Electron. 38 (1995) 1329.

[16] J.C. Zolper, J. Cryst. Growth 178 (1997) 157, and references therein.

[17] C.F. Chu, C.C. Yu, Y.K. Wang, J.Y. Tsai, F.I. Lai, S.C. Wang, Appl. Phys. Lett. 77 (2000) 3423.

[18] C.C. Yu, C.F. Chu, J.Y. Tsai, C.F. Lin, W.H. Lan, C.I. Chiang, S.C. Wang, Jpn. J. Appl. Phys. 40 (2001) L417.

[19] C.C. Yu, C.F. Chu, J.Y. Tsai, C.F. Lin, S.C. Wang, J. Appl. Phys. 92 (2002) 1881.

[20] H.W. Huang, C.C. Kao, J.Y. Tsai, C.C. Yu, C.F. Chu, J.Y. Lee, S.Y. Kuo, C.F. Lin, H.C. Kuo, S.C. Wang, Mater. Sci. Eng. B107 (2004) 237.

[21] C.F. Chu, C.C. Yu, H.C. Cheng, C.F. Lin, S.C. Wang, Jpn. J. Appl. Phys. 42 (2003) L147.

[22] M.D. McCluskey, L.T. Romano, B.S. Krusor, D.P. Bour, Appl. Phys. Lett. 72 (1998) 1730.

[23] Y.S. Lin, K.J. Ma, C.C. Yang, T.E. Weirich, J. Cryst. Growth 242 (2002) 35.

[24] C.J. Youn, T.S. Jeong, M.S. Han, J.W. Yang, K.Y. Lim, H.W. Yu, J. Cryst. Growth 250 (2003) 331.