Jpn. J. Appl. Phys. Vol. 41 (2002) pp. L226–L228
Part 2, No. 3A, 1 March 2002

On the Carrier Concentration and Hall Mobility in GaN Epilayers

Chih-Hsin Ko, Shoou-Jinn Chang, Yan-Kuin Su, Wen-How Lan[1], Jone F. Chen, Ta-Ming Kuan, Yao-Cong Huang, Chung-I. Chiang[1], Jim Webb[2] and Wen-Jen Lin[1]

Institute of Microelectronics & Department of Electrical Engineering, National Cheng Kung University, Tainan 70101, Taiwan, R.O.C.
[1]*Materials R&D Center, Chung-Shan Institute of Science & Technology, Tao-Yuan, Taiwan, R.O.C.*
[2]*Institute for Microstructural Sciences, National Research Council, Montreal Rd., Ottawa, Canada K1A 0R6*

(Received December 28, 2001; accepted for publication January 23, 2002)

The dependence of Hall mobility and carrier concentration in GaN epilayers on light illumination was examined. It was found that Hall mobility and electron concentration both increased after illumination with red laser (632.8 nm) and green laser (530 nm). However, no changes in Hall mobility and carrier concentration were found, if IR-laser (850 nm) was used. The results reveal that deep-level defects were excited and hence extra carriers were generated by light illumination. The influence is more pronounced for thinner films. These observations indicate that donor-like defect-related states were located 1.48 to 2.33 eV below the conduction band edge. [DOI: 10.1143/JJAP.41.L226]

KEYWORDS: GaN, Hall, defect, mobility, laser illumination

Recently, many researchers are interested in GaN-based wide bandgap III–V nitride compounds for their applications in light emitting diodes, laser diodes, and high power electronic devices that can be operated in high temperatures.[1–4] Although assessment of the properties and potential applications of nitrides is actively pursued to accelerate the device fabrication, detailed studies on some important parameters such as the relationship between defects and electronic properties have not been fully explored. The investigations of defects using yellow luminescence[4] (YL), persistent photoconductivity (PPC) effect,[5–9] and temperature variable Hall effect[9] have all been reported. YL is the normally unwanted luminescence signal, which appears in the photoluminescence (PL) spectrum of nitride-based materials. The YL band is regarded as a defect related feature. Shallow to deep donor level recombination[10] and deep donor to shallow acceptor level recombination[11] are the two widely accepted models for the presence of extensive YL. PPC is also considered as a consequence of defects generated phenomena and has detrimental effects on the performance of GaN/AlGaN high electron mobility transistor devices.[12] There are a couple of reports suggesting that PPC and YL phenomena in GaN have definite relations between each other.[13–15] In this work, we use lasers emitting at different wavelengths with different lasing intensities to excite GaN epitaxial layers. By using such a method, we report the differences in carrier concentration and mobility for GaN films with different epitaxial layer thickness.

Samples used in this study were all grown on (0001) sapphire (Al_2O_3) substrates by a low pressure organometallic vapor phase epitaxy (OMVPE) system.[16–20] The gallium and nitrogen sources were trimethylgallium (TMGa) and ammonia (NH_3), respectively. After annealing the sapphire substrate at 1100°C in H_2 ambient to remove surface contamination, a 30-nm-thick, low-temperature GaN nucleation layer was deposited onto the sapphire substrate at 520°C. The temperature was then raised to 1120°C to grow the unintentionally doped n-type GaN epitaxial layers with different thickness. The growth rate of the unintentionally doped n-type GaN epitaxial layers was kept at 2.2 μm/h. Samples were then cut into 5×5 cm^2, and indium dots were evaporated onto sample surfaces to form electrical contacts in Van der Pauw geometry for Hall effect measurements. The Hall measurements were conducted both in dark and under laser illumination. Three different lasers lasing at different wavelength (i.e. 632.8 nm, 530 nm and 850 nm) with different excitation intensities were used for the photo excited Hall measurement.

Figure 1 shows the measured dark Hall mobility (μ_D) and dark carrier concentration (C_D) as functions of GaN epitaxial layer thickness. It was found that when the GaN epitaxial layer thickness was 1.9 μm, the Hall mobility was only 44 cm^2·V^{-1}·s^{-1} and the carrier concentration was 7.3×10^{16} cm^{-3}. As the GaN epitaxial layer thickness increases, the Hall mobility increases rapidly while the carrier concentration decreases. When the GaN epitaxial layer thickness was 4.3 μm, the Hall mobility could reach 360 cm^2·V^{-1}·s^{-1} and the carrier concentration was reduced down to 2.0×10^{16} cm^{-3}. Such a result indicates that the crystal quality is poor for GaN epitaxial layers in the initial stage of growth. On the other hand, the crystal quality was significantly improved for the thick GaN epitaxial layers. Hall mobility and carrier concentration were also measured under illumination. Figures 2(a) and 2(b) shows the difference in carrier concentration for samples measured in dark (C_D) and under laser illumination (C_I), and the difference in Hall mobility for samples measured in dark (μ_D) and under laser illumination (μ_I), respectively. It is known that photons with a shorter wavelength have a larger energy. It is also known that there exist a large number of defect related trap states in the GaN epitaxial layers. Thus, more

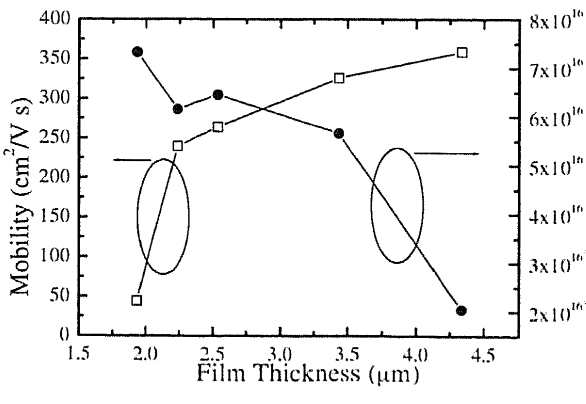
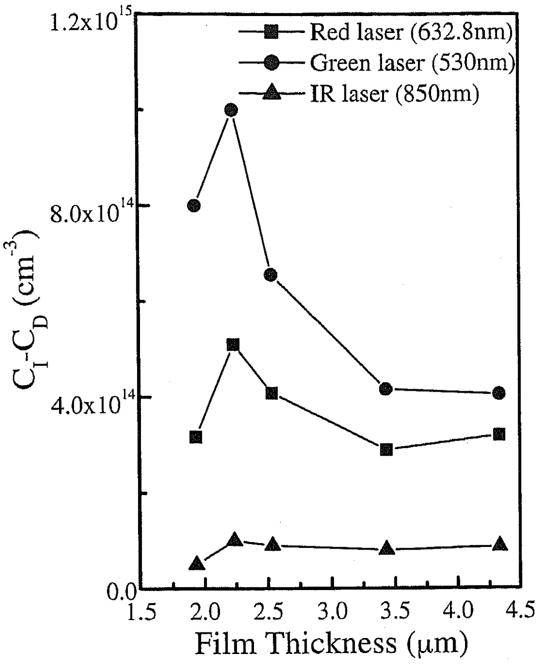
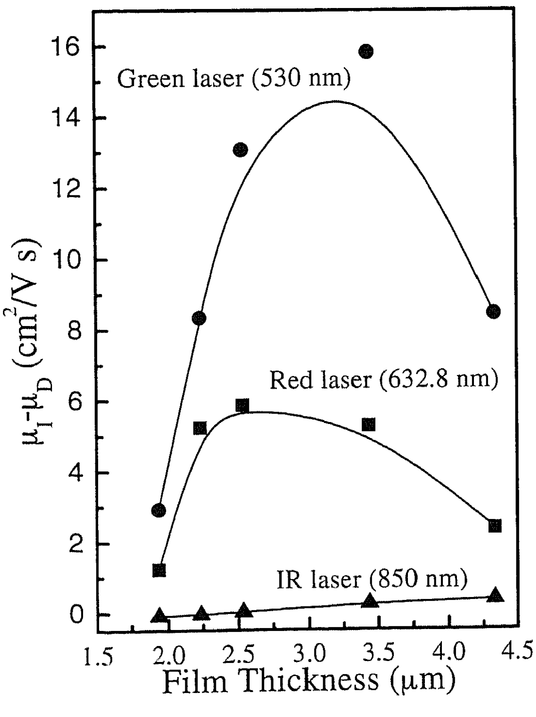


Fig. 1. Dependence of the Hall mobility and carrier concentration on the GaN epitaxial layer thickness measured in dark.

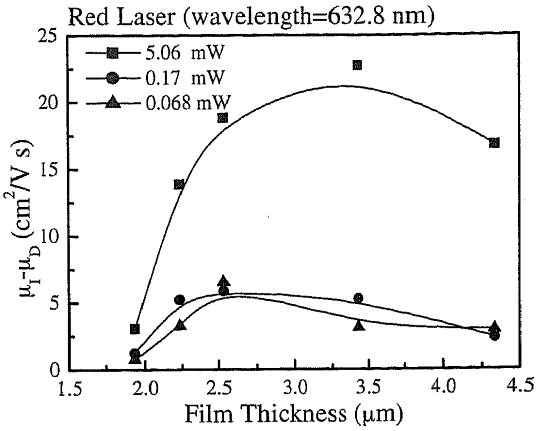


(a)

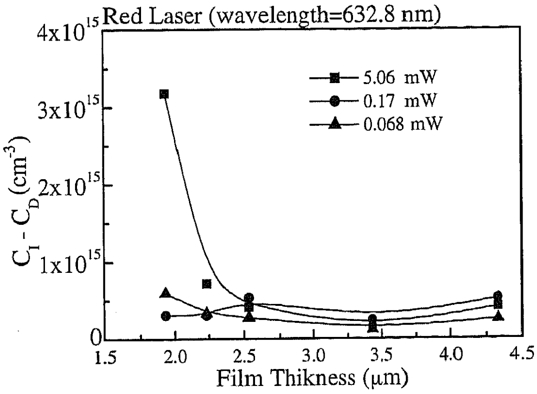


(b)

Fig. 2. The (a) carrier concentration difference under illumination (C_I) and in dark (C_D) and (b) mobility difference under illumination (μ_I) and in dark (μ_D) as functions of GaN epitaxial layer thickness.



(a)



(b)

Fig. 3. Light excitation intensity dependence of (a) Hall mobility difference (μ_I-μ_D), and (b) carrier concentration difference (C_I-C_D), measured in dark and under illumination by red laser.

trapped carriers could be activated and become photo generated carriers as the laser wavelength decreases. As a result, the difference in carrier concentration increases as the laser wavelength decreases, as shown in Fig. 2(a). Also, it was found that there is no appreciable change in carrier concentration while illuminated with infrared (IR) laser. Such an observation suggests no defect levels exist within 1.48 eV (i.e. $\lambda = 850$ nm) below the conduction band that can be excited by IR irradiation. Such a result also agrees well with the PPC measurement.[9] On the other hand, Hall mobility increases when the GaN epitaxial layers were illuminated with red laser light (632.8 nm or 1.96 eV), as shown in Fig. 2(b). Furthermore, it was found that such an increase was much more significant when the GaN epitaxial layers were illuminated with green laser light (530 nm or 2.33 eV) while no change in Hall mobility was found when the GaN epitaxial layers were illuminated with IR irradiation, as also shown in Fig. 2(b). The Hall mobility and carrier concentration both increase under visible light illumination suggests that there exist some donor-like defect-related states occupied by electrons in the GaN epitaxial layers. These negatively charged donor-like defect-related states also serve as scattering centers. Under illumination, the occupied electrons could be activated if the incoming photon energy is large enough. As a result, we could observe a larger electron concentration, as shown in Fig. 2(a). When the occupied electrons are activated, the donor-like defect-related states become electrically neutral with a much smaller scattering efficiency. Thus, we could also observe a larger Hall mobility at the same time, as shown in Fig. 2(b). Also, it was found that the Hall mobility difference increases first, reaches a maximum and then decreases again, as the GaN epitaxial layer thickness increases. When the GaN epitaxial layer is thin, the laser light can penetrate through the whole epilayer and most of the trapped electrons will be activated. Thus, the

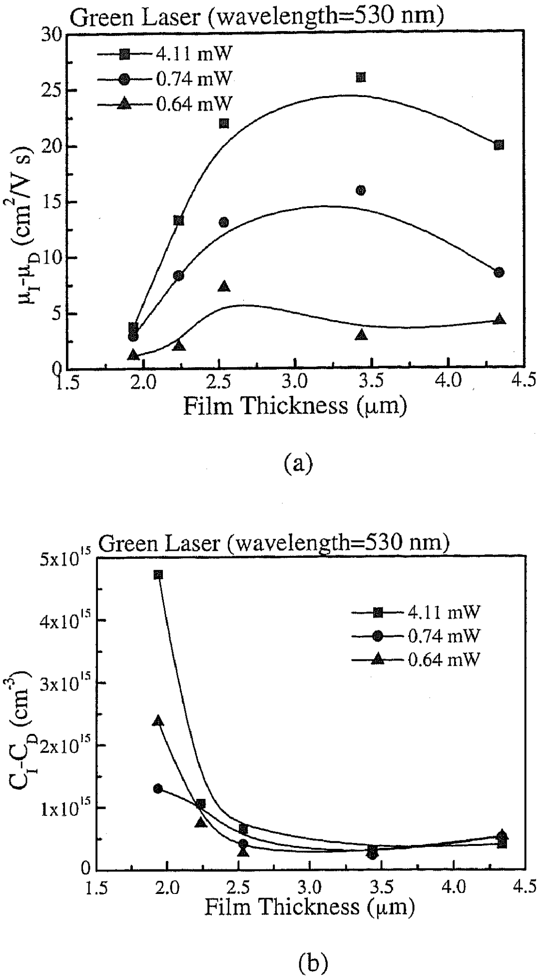


Fig. 4. Light excitation intensity dependence of (a) Hall mobility difference (μ_I-μ_D), and (b) carrier concentration difference (C_I-C_D), measured in dark and under illumination by green laser.

Hall mobility difference increases as the GaN epitaxial layer thickness increases. For thick GaN epitaxial layers, the incoming photons will be absorb rapidly due to the large number of donor-like defect-related states in the epilayer. As a result, only those trapped electrons near the sample surface will be activated and only those donor-like defect-related states near the sample surface will become electrically neutral with a smaller scattering efficiency. On the other hand, electrons will still occupy those donor-like defect-related states away from the sample surface. Thus, those donor-like defect-related states away from the sample surface will still be charged negatively with a large scattering efficiency. As a result, the measured Hall mobility difference will decrease as the GaN epitaxial layer thickness increases. When the Hall mobility difference reaches its maximum, we call it level off. Thus, as the photon energy increases, the penetration depth will decrease and thus level off will occur when the epitaxial layer film thickness is larger, as shown in Fig. 2(b). Different excitation levels also enhance the illumination effect differently. Figures 3 and 4 show the samples illuminated by variable excitation intensities. As shown in Figs. 3(a) and 4(a), the mobility difference between illuminated sample and non-illuminated sample (μ_I-μ_D) increases with the excitation intensity. The Hall carrier concentration difference (C_I-C_D) increases with the illumination intensity in near substrate region too, but levels off rapidly, as shown in Figs. 3(b) and 4(b). These results again indicate that some donor-like defect-related states exist in the range of 1.48 to 2.33 eV below the conduction band edge of GaN epitaxial layers, and the density of these defect-related states was higher for thinner films. Such a range also agrees with the reported YL observed from PL measurement.

In conclusion, the influence of light illumination on the defect distribution as determined by Hall measurement has been investigated in GaN epitaxial layers. Our results indicate that the presence of donor-like defect-related states exist in the range of 1.48 to 2.33 eV below the conduction band edge for the as deposited GaN films.

This work is partially supported by National Science Council under the contract NSC-892218E006095.

1) I. Akaski, H. Amano, M. Kito and K. Hiramatsu: J. Lumin. **48** (1991) 666.
2) S. Nakamura, T. Mukai and M. Senoh: Appl. Phys. Lett. **64** (1994) 1687.
3) H. Morkoc, S. Strite, G. B. Gao, M. E. Lin, B. Sverdlov and M. Burns: J. Appl. Phys. **76** (1994) 1363.
4) C. V. Reddy, K. Balakrishnan, H. Okumura and S. Yoshida: Appl. Phys. Lett. **73** (1998) 244.
5) M. A. Khan, J. N. Kuznia, D. T. Olson, J. M. Van Hove, M. Blasinghame and L. F. Reitz: Appl. Phys. Lett. **60** (1992) 2917.
6) P. Kung, X. Zhang, D. Walker, A. Saxler, J. Piotrowskr, A. Rogalski and M. Razeghi: Appl. Phys. Lett. **67** (1995) 3792.
7) J. Z. Li, J. Y. Lin, H. X. Jiang, A. Salvador, A. Votchkarev and H. Morkoc: Appl. Phys. Lett. **69** (1996) 1474.
8) H. M. Chen, Y. F. Chen, M. C. Lee and M. S. Feng: J. Appl. Phys. **82** (1997) 2378.
9) G. Li, S. J. Chua and W. Wang: Solid State Commun. **111** (1999) 659.
10) T. Ogino and M. Aoki: Jpn. J. Appl. Phys. **19** (1980) 2395.
11) E. R. Glaser, T. A. Kennedy, K. Doverspike, L. B. Rowland, D. K. Gaskill, J. A. Freitas, Jr., M. Asif Khan, D. T. Olson, J. N. Kuznia and D. K. Wickenden: Phys. Rev. B **51** (1995) 326.
12) J. Z. Li, J. Y. Lin, H. X. Jiang, M. A. Khan and Q. Chen: J. Vac. Sci. & Technol. B **15** (1997) 1117.
13) H. M. Chen, Y. F. Chen, M. C. Lee and M. S. Feng: Phys. Rev. B **56** (1997) 899.
14) H. M. Chen, Y. F. Chen, M. C. Lee and M. S. Feng: Phys. Rev. B **56** (1997) 6942.
15) D. W. Jenkins and J. D. Dow: Phy. Rev. B **39** (1989) 3317.
16) J. K. Sheu, J. M. Tsai, S. C. Shei, W. C. Lai, T. C. Wen, C. H. Kou, Y. K. Su, S. J. Chang and G. C. Chi: IEEE Electron. Device Lett. **22** (2001) 460.
17) C. H. Chen, S. J. Chang, Y. K. Su, G. C. Chi, J. Y. Chi, C. A. Chang, J. K. Sheu and J. F. Chen: IEEE Photon. Technol. Lett. **13** (2001) 848.
18) W. C. Lai, S. J. Chang, M. Yokoyama, J. K. Sheu and J. F. Chen: IEEE Photon. Technol. Lett. **13** (2001) 559.
19) Y. K. Su, Y. Z. Chiou, F. S. Juang, S. J. Chang and J. K. Sheu: Jpn. J. Appl. Phys. **40** (2001) 2996.
20) C. H. Chen, S. J. Chang, Y. K. Su, G. C. Chi, J. K. Sheu and I. C. Lin: Jpn. J. Appl. Phys. **40** (2001) 2762.