Available online at www.sciencedirect.com
ScienceDirect
Journal of Crystal Growth 305 (2007) 55–58
JOURNAL OF CRYSTAL GROWTH
www.elsevier.com/locate/jcrysgro

Improvement of efficiency and ESD characteristics of ultraviolet light-emitting diodes by inserting AlGaN and SiN buffer layers

G.S. Huang[a,*], H.C. Kuo[a], M.H. Lo[a], T.C. Lu[a], J.Y. Tsai[b], S.C. Wang[a]

[a]Department of Photonics & Institute of Electro-Optical Engineering, National Chiao Tung University, 1001 TA Hsueh Road, Hsinchu 300, Taiwan, ROC
[b]Highlink Technology Corporation, No. 13, Ke Jung Road, Chu-Nan Site, Hsinchu Science Park, Chu-Nan, Miao-Li County 350, Taiwan, ROC

Received 4 October 2006; received in revised form 19 March 2007; accepted 11 April 2007
Communicated by K. M. Lau
Available online 14 April 2007

Abstract

We have studied the effect of the AlGaN insertion and SiN buffer layers of ultraviolet light-emitting diodes (UVLEDs) on efficiency and electrostatic discharge (ESD) characteristics of UVLEDs grown by metalorganic chemical vapor deposition. The etching pit density was reduced from $3.6\times10^{8}\,cm^{-2}$ in conventional samples to $1.6\times10^{7}\,cm^{-2}$ in UVLEDs grown with the AlGaN insertion layer and SiN buffer layer. During the ESD tests at the negative biases of 3000 V, the live percentage of UVLEDs increased from 67% in conventional samples to 86% in samples with AlGaN insertion layers and SiN buffer layers. In addition, the device shows a low leakage current of 1.1×10^{-8} A at -5 V and the light output power was 70% higher than the conventional UVLEDs at an injection current of 20 mA.

PACS: 61.72.Ff; 81.15.Gh; 73.61.Ey; 68.37.Hk

Keywords: A1. Defects; A3. Metalorganic chemical vapor deposition; B1. Nitrides; B3. Light emitting diodes

1. Introduction

III–V nitrides are of great interest for using in blue/green and ultraviolet light-emitting diodes (UVLEDs) and laser diodes (LDs) [1–4]. The UVLEDs with emission wavelengths in 300–390 nm range are ideal pumps for fluorescent display devices. This is one of the most promising ways for producing solid state white light. Short wavelength UV light can be additionally used in applications such as optical data storage, microscopes, and lithography instruments. In most cases, these nitride-based UVLEDs were grown on sapphire substrates. Although nitride-based UVLEDs have been developed for several years, many problems still remain to be solved. For example, large mismatches in lattice constants between GaN epitaxial layers and the underneath sapphire substrates result in an epitaxial layer with poor quality. It has also been shown that GaN-based UVLEDs often suffer from electrostatic discharge (ESD) due to the insulating nature of sapphire substrates [5,6]. Normally a thin low-temperature (LT) GaN nucleation layer prior to the epitaxial growth was deposited to overcome a relatively large lattice mismatch [1,2]. However, the large dislocation density still remains to hinder the performance of devices. In order to reduce dislocation density further, the epitaxial lateral overgrowth (ELO) was proposed to grow a 2–3 μm-thick GaN layer on a sapphire substrate prior to the sample patterning and then regrowth [7]. However, such a procedure is relatively complex that inevitably results in a low production yield. Recently, it has been reported that one can reduce the defect density in nitride-based epitaxial layers using GaN–SiN as the nucleation layer [8–15]. Many nanometer-sized porous SiN layer probably serves to enhance the lateral growth, which is quite similar to that in ELO to reduce dislocation density. On the other hand, polarization-induced electric fields between the AlGaN and GaN lead to a significant increase of the sheet carrier concentration and narrower confinement of the two-dimensional

*Corresponding author. Tel.: +886 035712121 56327;
fax: +886 035716631.
E-mail address: gshuang@mail.nctu.edu.tw (G.S. Huang).

0022-0248/$ - see front matter
doi:10.1016/j.jcrysgro.2007.04.022

electron gases (2DEGs). Such a 2DEG can be used to spread the current effectively, and this AlGaN/GaN heterostructure can also be used to confine the holes, which escaped from MQW. Thus, the injection current overflow was diminished and the light emission efficiency was greatly improved [16]. In this paper, the UVLEDs with a SiN buffer layer and an AlGaN insertion layers were prepared. Physical, optical, and electrical properties of the fabricated UVLEDs with different underlying GaN layers will also be reported.

2. Experiments

Samples used in this paper were all grown on c-face (0 0 0 1) 2-in sapphire substrates by metalorganic chemical vapor deposition. During the growth, trimethylgallium (TMGa), trimethylindium (TMIn), trimethylaluminum (TMAl), and ammonia (NH_3) were used as the gallium, indium, aluminum, and nitrogen sources, respectively. Bis-cyclopentadienyl magnesium (Cp_2Mg) and silane (SiH_4) were used as the p-type and n-type doping sources, respectively. Prior to the epitaxial growth, the sapphire substrates were annealed at 1100 °C in H_2 ambient to remove surface contamination. Three different structures were grown for comparisons. Sample I consisted of a 30-nm-thick GaN nucleation layer grown onto the sapphire substrates at 535 °C, an 1.5-μm-thick undoped GaN layer grown at 1070 °C, an 1.3-μm Si-doped GaN grown at 1070 °C, a 0.1-μm–thick Si-doped $Al_{0.08}Ga_{0.92}N$ layer grown at 1000 °C followed by an 1.3-μm Si-doped GaN grown at 1070 °C, the quantum well region consisted of five periods of 20-nm-thick GaN barrier layers, and 2-nm-thick $In_xGa_{1-x}N$ well layers with $x \sim 5\%$ followed by a 35-nm-thick Mg-doped $Al_{0.16}Ga_{0.84}N$ layer grown at 950 °C and a 0.12-μm-thick Mg-doped GaN cap layer grown at 950 °C. For sample II, an additional 0.1-μm-thick undoped $Al_{0.08}Ga_{0.92}N$ layer was inserted into the undoped GaN bulk layer with 0.2 μm thickness under the n-GaN layer based on the structure of the sample I. Meanwhile, Fig. 1 shows sample III with a SiN buffer layer deposited before the GaN nucleation layer based on the structure of sample II.

The surface of these samples was then etched until n-GaN exposed. Indium–tin oxide (ITO) and Ni/Au were subsequently evaporated onto the sample surface to serve as p-type electrode. Ti/Al/Ni/Au contact was deposited onto the exposed n-GaN layer to serve as the n-type electrode. The epitaxial wafers were lapped down and then scribed to the fabrication of $300 \times 300\,\mu m^2$ UVLEDs. The *I–V* characters and optical properties were investigated. In order to investigate the quality of n-GaN layer of samples, photoelectrochemical (PEC) etching was performed by 2.2 M KOH solution for 30 min. Scanning electron microscopy (SEM) was then used to check the surface of samples after the PEC etching. Negative biases were applied to the UVLEDs to examine their ESD sustainability.

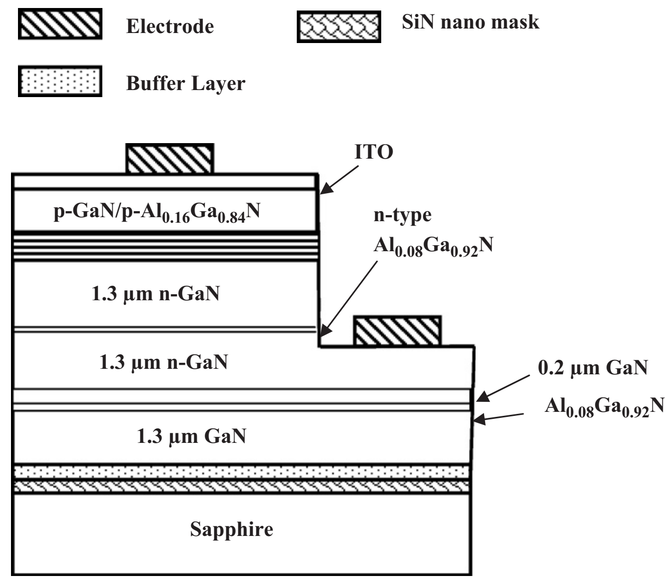

Fig. 1. The schematic diagram of UVLED sample III.

3. Results and discussion

Fig. 2(a–c) shows SEM images of the UVLED samples I, II, and III, respectively. As shown in Fig. 2(b), it was found that the surface morphology of the LED with AlGaN insertion was rough and the result is similar to conventional UVLED (Fig. 2(a)). Fig. 2(c) clearly shows that the LED with SiN buffer has the flat surface morphology and lower threading dislocation (TD) density. The TD densities of all samples calculated from the SEM images were 3.6×10^8, 3.9×10^8, and $1.6 \times 10^7\,cm^{-2}$, respectively. Fig. 2(b) shows lightly higher TD density than the conventional UVLED. It was found that the TD density was not reduced by inserting an undoped AlGaN layer onto the GaN film. However, it was found that there were not any deep V-shape defects in sample II. Fig. 2(c) shows that the TD density was effectively suppressed by inserting the SiN buffer. It was found that the TD density can be lowered one order of magnitude than the conventional UVLED by inserting the SiN buffer layer. The density of dislocations is remarkably lower in GaN layers grown after SiN buffer than the density in layers obtained using the conventional process [13–15].

Fig. 3 shows the live percentages of three batches of 1000 testing samples when the negative biases applied on the three UVLEDs from 100 to 3000 V. Here we define the devices are not live in which the leakage current is larger than 1 μA in the reverse voltage region even through the UVLED survived at this reverse ESD pulse voltage. The live percentage of sample I decreased from 82% to 72% when the negative bias increases from 100 to 200 V, and then decreased slowly to 67% when the negative bias increased further to 3000 V. The live percentage of sample II was about 95% at initial negative bias of 100 V and remained 82% at negative bias of 3000 V. The improved

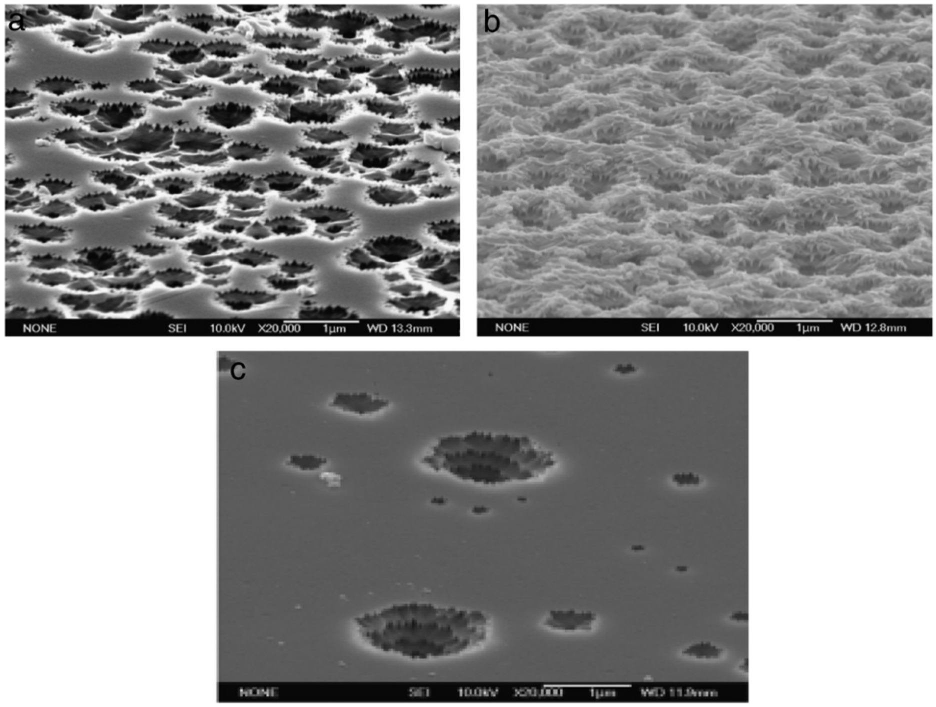

Fig. 2. The SEM top view images of (a) sample I, (b) sample II, (c) sample III treated with 2.2 M KOH solution PEC etching for 30 min.

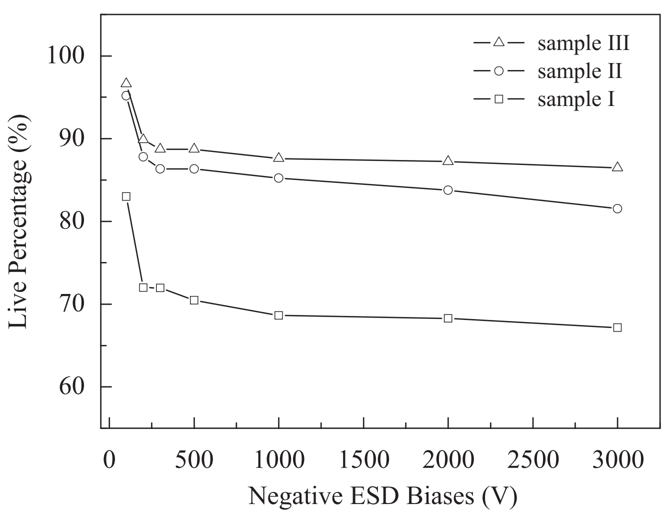

Fig. 3. The live percentage of samples I, II, and III as function of negative ESD biases applied onto the UVLEDs.

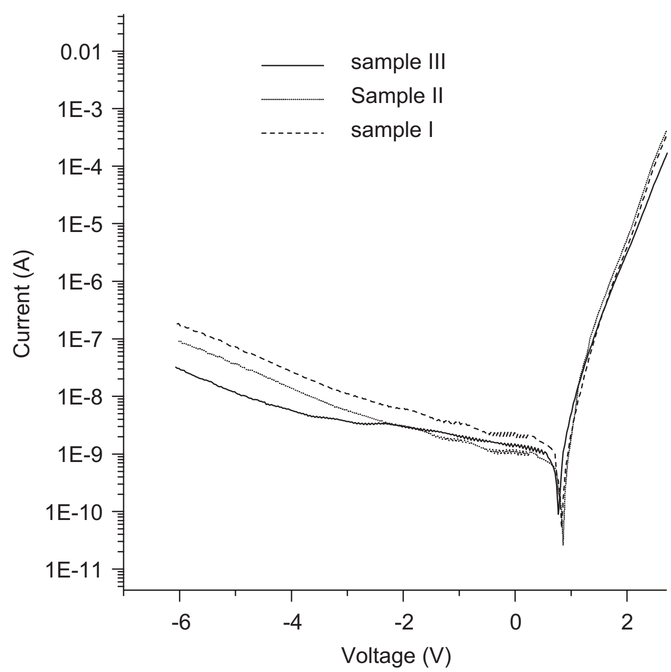

Fig. 4. Leakage current as function of reverse voltage of UVLED samples I, II, and III.

ESD characteristics of the UVLED with AlGaN insertion layer could be due to higher current tolerance and the reduced strain between the GaN layer and sapphire substrate. The live percentage of sample III was about 97% at initial negative bias of 100 V and remained 86% at negative bias of 3000 V. The highest ESD survival rate in sample III was probably the results of further improved GaN quality with lower TD density.

Fig. 4 shows the reverse voltage versus current characteristics of sample I, II, and III. It is found that the leakage currents of all UVLEDs at −5 V were in the order of magnitude of 10^{-8} A. The leakage current of sample III is the lowest about 1.1×10^{-8} A. Fig. 5 shows the effects of injection current on the light output power of UVLED samples. The light output powers of sample II and III were greater than conventional sample I at an injection current of 20 mA, respectively. The light output powers of sample II and III increased 25% and 70% more than sample I, respectively. Fig. 6 shows the electroluminescence spectra of three LED samples at the injection current of 20 mA. The three UVLED samples showed the same EL peak of

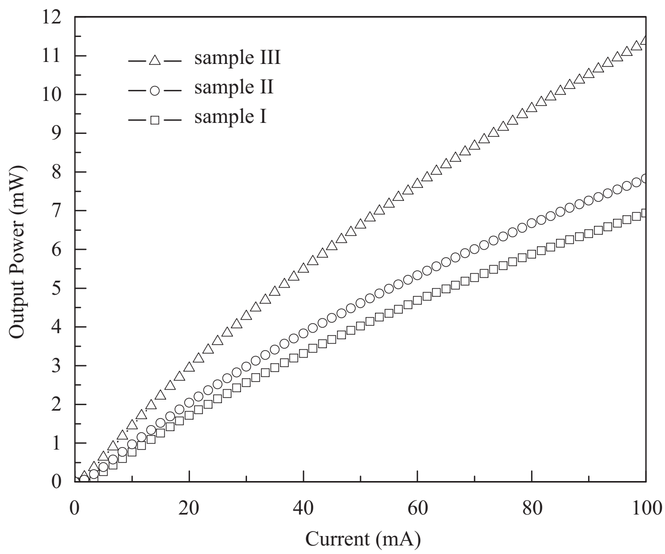

Fig. 5. The effect of injection current on the light output power of UVLED samples I, II, and III.

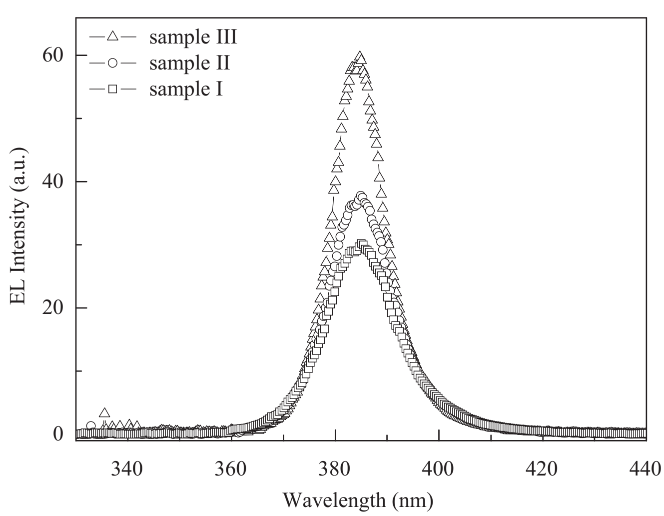

Fig. 6. The electronic emission spectra of UVLED samples I, II, and III at an injection current of 20 mA.

385 nm since the growth conditions of active region of multiple quantum wells were the same. In addition, sample III showed a narrower full width at half maximum (FWHM) of spectrum (about 11 nm) than that of the sample I (about 15 nm). The surface morphology of n-type GaN has been improved by inserting SiN buffer layer. The narrower FWHM of sample III should be related to more uniform indium distribution than that of sample I.

4. Conclusion

In conclusion, we studied the effects of an AlGaN insertion layer and SiN buffer of UVLEDs on the efficiency and ESD characteristics of UVLED samples. For the optimized AlGaN insertion layer and SiN buffer, the leakage currents of all UVLEDs at −5 V were in the order of magnitude of 10^{-8} A. Meanwhile, the light output power of UVLED increase 70% compared with the conventional UVLED sample. The live percentage of UVLED remains about 86% at negative bias of 3000 V higher than that of conventional UVLED sample of 67%. PEC etching confirmed that the improvement of the optical properties was accompanied by a reduction in the dislocation density.

Acknowledgement

This work was financially supported by the MOE ATU program and in part by the National Science Council of Republic of China (ROC) in Taiwan under contract No. NSC 95-2120-M-009-008 and No. NSC 94-2215-E-009-082.

References

[1] S. Nakamura, T. Mukai, M. Senoh, J. Appl. Phys. 76 (1994) 8189.
[2] S. Nakamura, M. Senoh, T. Mukai, Jpn. J. Appl. Phys. 32 (1993) L8.
[3] T. Nishida, H. Saito, N. Kobayashi, Appl. Phys. Lett. 78 (2001) 3297.
[4] C.Q. Chen, J.W. Yang, M.-Y. Ryu, J.P. Zhang, E. Kuokstis, G. Simin, M.A. Khan, Jpn. J. Appl. Phys. Lett. 41 (2002) 1924.
[5] S.J. Chang, C.H. Chen, Y.K. Su, J.K. Sheu, W.C. Lai, J.M. Tsai, C.H. Liu, S.C. Chen, IEEE Electron. Device Lett. 24 (2003) 129.
[6] G. Meneghesso, S. Podda, M. Vanzi, Microelectron. Reliabil. 41 (2001) 1609.
[7] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, Y. Sugimuto, T. Kozaki, H. Umemoto, M. Sano, K. Chocho, Appl. Phys. Lett. 72 (1998) 211.
[8] K. Uchida, K. Nishida, M. Kondo, H. Munekata, J. Crystal Growth 189–190 (1998) 270.
[9] T. Kachi, K. Tomita, K. Itoh, H. Trando, Appl. Phys. Lett. 72 (1998) 704.
[10] Y.B. Lee, T. Wang, Y.H. Liu, J.P. Ao, Y. Izumi, Y. Lacroix, H.D. Li, J. Bai, Y. Naoi, S. Sakai, Jpn. J.Appl. Phys. 41 (2002) 4450.
[11] S.E. Park, S.M. Lim, C.R. Lee, C.S. Kim, B.O., J. Crystal Growth 249 (2003) 487.
[12] S. Sakai, T. Wang, Y. Morishima, Y. Naoi, J. Crystal Growth 221 (2000) 334.
[13] C.H. Kuo, S.J. Chang, Y.K. Su, C.K. Wang, L.W. Wu, J.K. Sheu, T.C. Wen, W.C. Lai, J.M. Tsai, C.C. Lin, Solid State Electron. 47 (2003) 2019.
[14] R.C. Tu, C.C. Chuo, S.M. Pan, Y.M. Fan, C.E. Tsai, T.C. Wang, C.J. Tun, G.C. Chi, B.C. Lee, C.P. Lee, Appl. Phys. Lett. 83 (2003) 3608.
[15] S. Haffouz, V. Kirilyuk, P.R. Hageman, L. Macht, J.L. Weyher, P.K. Larsen, Appl. Phys. Lett. 79 (2001) 2390.
[16] C.-H. Chen, J. Vac. Sci. Technol. A 24 (2006) 1001.