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Research Article

Fabrication of GaN-Based White Light-Emitting Diodes on Yttrium Aluminum Garnet-Polydimethylsiloxane Flexible Substrates

Lung-Chien Chen, Wen-Wei Lin, and Jun-Wei Chen

Department of Electro-Optical Engineering, National University of Technology, 1, Sec. 3, Chung-Hsiao E. Road, Taipei 106, Taiwan

Correspondence should be addressed to Lung-Chien Chen; ocean@ntut.edu.tw

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This study concerns the characteristics of white GaN-based light-emitting diode (LED) on flexible substrates. The thin film GaN-based blue LEDs were directly transferred from sapphire onto the flexible polydimethylsiloxane (PDMS) substrates by laser lift-off (LLO) process. The PDMS substrates were incorporated 10–40% cerium doped yttrium aluminum garnet phosphor, YAG:Ce^{3+}, and formed the GaN-based white LEDs. The white LEDs prepared by the GaN-based LEDs on the YAG-PDMS substrates reveal one peak at 470 nm corresponding to the emission of the GaN-based LED and a broadband included five weak peaks caused by YAG:Ce^{3+} phosphors.

1. Introduction

LEDs are regarded as the most important light source in next-generation solid-state lighting to advantages in energy efficiency, long life, high reliability, and multiple applications [1, 2]. In recent years, due to the more benefits with flexible substrate, the fabrication of lighting sources on flexible substrates has been studied vigorously to develop, such as biomedical applications, deformable display, wearable devices, and flexible LEDs [3–6].

Several approaches have presented flexible light-emitting diodes (F-LEDs) by transferring microstructured GaAs/GaN to flexible substrates [7–10]. And the majority methods have produced flexible and highly efficient thin film GaN-based LEDs by laser lift-off (LLO) technology [11–15].

In this study, we have prepared a polydimethylsiloxane (PDMS) as a substrate which had the advantages of being flexible, low cost, good chemicophysical properties and being good optically transparent. The fabrication of thin film GaN-based light-emitting diodes (GaN-based LEDs) was transferred from sapphire to flexible substrate by LLO method and produced the white light-emitting diode device.

2. Experimental

2.1. PDMS Substrate Production Process. PDMS solution was produced by mixing silicone resin agent (A agent) and curing agent (B agent) into liquid in weight ratio for 10 : 1. Then, the yellow phosphor was incorporated into the PDMS solution and stirred uniformly. Afterward, the PDMS incorporated YAG phosphor solution was placed in a vacuum chamber for 30 min so that bubbles disappeared. Polytetrafluoroethene (PTFE) is sprayed on the sapphire substrate to avoid PDMS sticking on sapphire. Then, PDMS was uniformly coated on a sapphire substrate by spin coater (speed of 300 rpm and a coating time of 40 sec). Subsequently, the PDMS substrate was treated at temperature of 120°C for 30 min to produce PDMS substrate. Finally, the cured PDMS substrate incorporated YAG phosphor (YAG-PDMS substrate) was removed from the sapphire substrate to produce white LED.

2.2. Preparation of White LED. The GaN-based light-emitting diode comprised a 3 μm thick GaN:Si layer, five pairs of undoped InGaN/GaN multiple-quantum-wells (InGaN-GaN MQWs), and a 0.5 μm thick layer of GaN:Mg sequentially on a (0001) oriented patterned sapphire substrate with a GaN buffer layer that was grown by metal-organic chemical

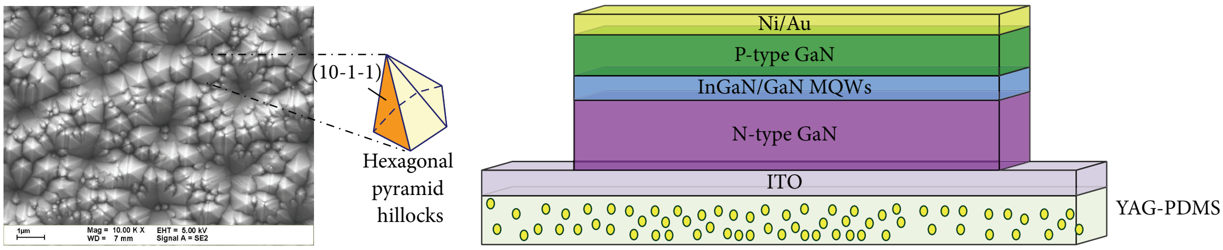


FIGURE 1: (a) Surface of the n-GaN epitaxial layer after KOH solution etching and (b) GaN-based LED after LLO process was mounted on flexible YAG-PDMS substrate.

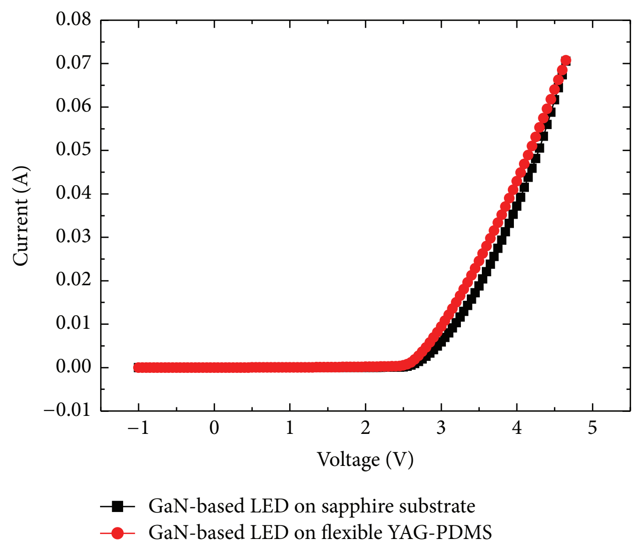


FIGURE 2: *I-V* curves of LEDs on sapphire substrate and YAG-PDMS substrate, respectively.

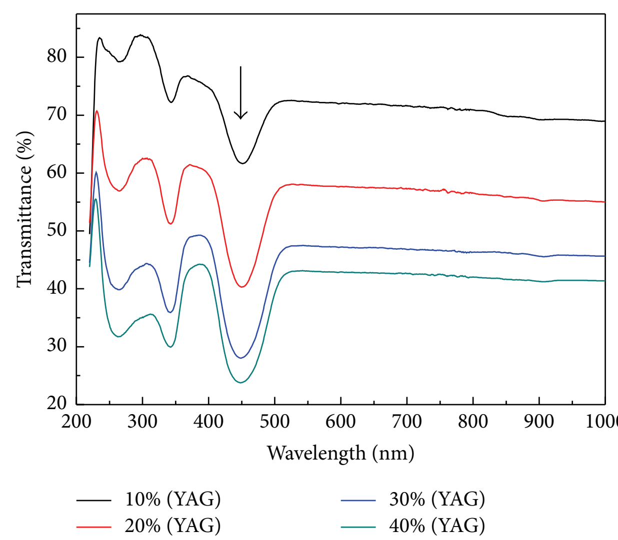


FIGURE 3: Transmittance spectra of YAG-PDMS substrates with various YAG incorporation amount.

vapor deposition (MOCVD). Ni/Au (45 nm/15 nm thickness) layers are deposited on the p-GaN as ohmic contact, respectively. Next, p-GaN/InGaN-GaN MQWs/n-GaN structure is separated from the sapphire substrate by LLO method using 248 nm KrF laser after bonding to glass temporary substrate. The wafer was etching using KOH solution for 30 min to remove residue gallium oxide. The surface of the n-GaN epitaxial layer was observed hexagonal pyramid hillocks, as shown in Figure 1(a). Then, the structure was transferred onto the YAG-PDMS substrate with ITO contact layer to complete the GaN-based white LEDs. Figure 1(b) demonstrates the structure of the GaN-based LEDs on the YAG-PDMS substrate.

3. Results and Discussion

Figure 2 plots *I-V* curves of LED on sapphire substrate and YAG-PDMS substrate, respectively. *I-V* characteristics of the GaN-based LED on the YAG-PDMS substrate exhibited less turn-on voltage and resistivity than that of the GaN-based LED on the sapphire substrate. The comparably good electrical characteristics of the GaN-based LED on flexible PDMS substrates that proposed the laser lift-off technology would not degrade device electrical performance and have better trend owing to the vertical operating device. However, leakage was observed at low forward bias. That means the stress between the GaN epitaxial layer and the flexible YAG-PDMS substrate due to removing the sapphire substrate.

Figure 3 shows the transmittance spectra of YAG-PDMS substrates with various YAG incorporation amount in weight percentage. The transmittance decreases when the incorporation amount in PDMS increases owing to the absorption by the YAG phosphors. There is a most deep absorption valley at around 450 nm in all samples, assigned to the 4f ($^2F_{5/2}$) → $5d_2$ transitions of Ce^{3+} ions, as shown in Figure 3. Therefore, the YAG-PDMS is suitable for the exciting source of the GaN LED with emitting wavelength of about 450 nm.

Figure 4 shows the normalized electroluminescence (EL) spectra of the LEDs on YAG-PDMS with different incorporated concentration at the RT. According to Figure 4, the RT EL spectra of the GaN LEDs on the YAG-PDMS substrates reveal one peak, denoted as peak *A*, that is, at 470 nm, and a broadband included five weak peaks, denoted as peaks I_1, I_2, I_3, I_4, and I_5 at 2.56 eV (484 nm), 2.36 eV (525 nm), 2.27 eV (547 nm), 2.15 eV (578 nm), and 2.02 eV (615 nm), respectively. The intensity of the broadband increases when

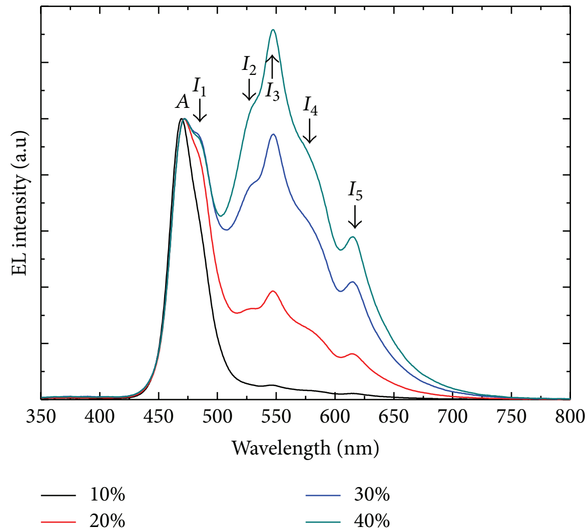
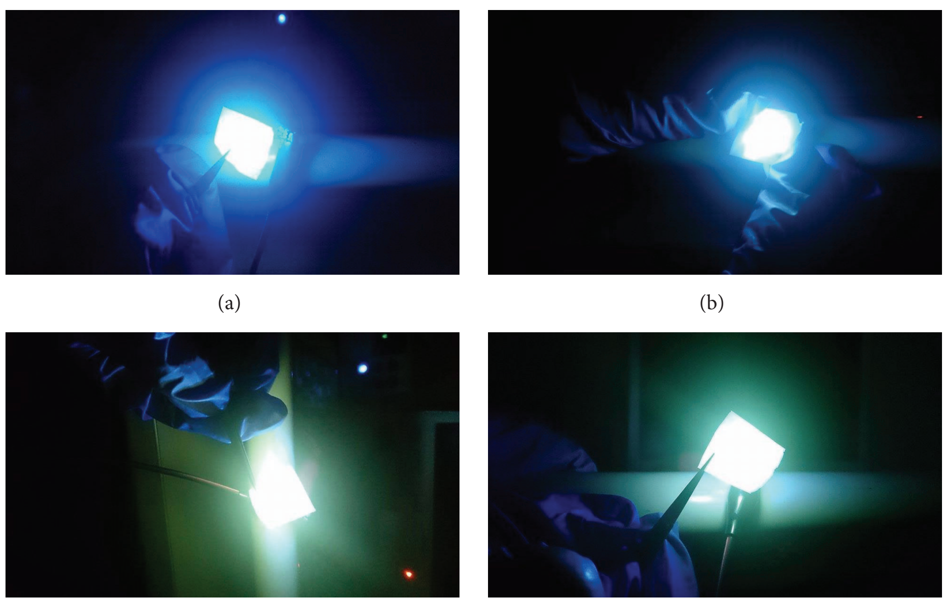


FIGURE 4: EL spectra obtained with different incorporation amount.



(a) (b) (c) (d)

FIGURE 5: Operating photos of LED on YAG-PDMS substrates with various incorporation amounts: (a) 10%, (b) 20%, (c) 30%, and (d) 40% concentration of phosphor.

the incorporated concentration increases from 10% to 40%. Peak A is attributed to the GaN blue LED with 470 nm emitting wavelength as exciting light source. The broadband that included five weak peaks may be corresponding to $^5D_4 \rightarrow {}^7F_6$, $^5D_1 \rightarrow {}^2F_5$, $^5D_4 \rightarrow {}^7F_5$, $^5D_4 \rightarrow {}^7F_4$, and $^5D_4 \rightarrow {}^7F_3$ level transitions of Ce^{3+} ions in the YAG phosphors, respectively [16–18].

The color of EL is nearly white, as shown in Figure 5. The color is from white-bluish to white-yellowish when the incorporation amount of YAG phosphors in PDMS substrates increases from 10% to 40%. The white light may have contributed to the wide emission band ranging from 400 to 750 nm. The chromaticity coordinates of the YAG phosphors at 10, 20, 30, and 40% in PDMS substrates are presented in the CIE (Commission Internationale De L'éclairage) chromaticity diagram, as shown in Figure 6. With the increasing incorporated concentration of YAG, the chromaticity coordinates move in white light area from $x = 0.3666$, $y = 0.3446$ (correlated color temperature (CCT) = 6700 K) for the sample at 10% to $x = 0.3280$, $y = 0.3762$ (CCT = 5666 K) for the sample at 40%. The variation of CCT is only ~15% when the incorporated concentration of YAG increases from 10% to 40%. Therefore, the YAG phosphors in PDMS substrate are suitable for flexible solid-state lighting because it has a stable white light color when the incorporated concentration is in the range of 10–40 wt%.

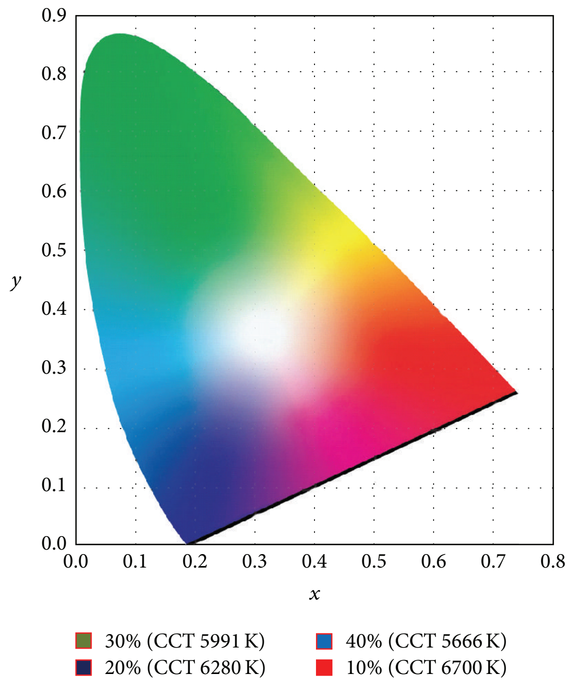


Figure 6: Chromaticity coordinates of the GaN-based LEDs on the YAG-PDMS substrates.

4. Conclusions

In summary, characteristics of white GaN-based LEDs on YAG-PDMS substrates are reported. The white light may have contributed to the wide emission band ranging from 400 to 750 nm. The chromaticity coordinates of the YAG phosphors at 10, 20, 30, and 10% in YAG-PDMS substrates are presented in the CIE chromaticity diagram. With the increasing incorporated concentration of YAG, the chromaticity coordinates move in white light area from $x = 0.3666$, $y = 0.3446$ (CCT = 6700 K) for the sample at 10% to $x = 0.3280$, $y = 0.3762$ (CCT = 5666 K) for the sample at 40%. Therefore, the YAG phosphors in PDMS substrate are suitable for flexible solid-state lighting because it has a stable white light color when the incorporated concentration is in the range of 10–40 wt%.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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