Enhancing the Light Extraction of $(Al_xGa_{1-x})_{0.5}In_{0.5}P$-Based Light-Emitting Diode Fabricated via Geometric Sapphire Shaping

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***Abstract*—AlGaInP-based light-emitting diodes (LEDs) with a transparent sapphire substrate were fabricated by the glue-bonding (GB) method. This transparent sapphire substrate is a geometric shaping structure by wet etching processes. Furthermore, the n-side-up surface has a nano-roughened texture by natural mask and chemical wet etching processes. The light output of this novel LED structure could be enhanced about 26.7% (at 350 mA) due to the higher light extraction as compared with the conventional GB-LEDs.**

***Index Terms*—AlGaInP-based light-emitting diodes (LEDs), geometric sapphire shaping light-emitting diodes (GSS-LEDs), glue bonding (GB), sapphire chemical wet etching.**

I. INTRODUCTION

THE $(Al_xGa_{1-x})_{0.5}In_{0.5}P$-based quaternary materials with a visible spectrum from red to yellow-green are grown on a GaAs substrate. Recently, high-performance AlGaInP-based optical devices were widely used for many different applications such as optical communications, the automobile industry, traffic lights, full-color displays, and interior and exterior display [1], [2]. Although, the AlGaInP-based material has been developed for many years [3], its internal quantum efficiency (η_i) closely approaches 95% due to the excellent epitaxy technique [4]. Though the AlGaInP-based light-emitting diodes (LEDs) have higher internal quantum efficiency than the GaN-based LEDs, the light extraction efficiency is less than GaN-based LEDs due to the large difference of the refractive index between the GaP window layer $(n = 3.2)$ and air $(n = 1)$. It will induce the smaller critical angle $(\theta_c)[\theta_c = \sin^{-1}(n_{\mathrm{air}}\text{–}n_{\mathrm{GaP}})] \sim 18.2^\circ$ for light output and more of the total internal reflection (TIR) effect. In addition, there are some inherent drawbacks to the conventional AlGaInP-based LEDs such as the limited barrier height in the GaInP–AlGaInP quantum-well structures, larger thermal resistance due to the large mass difference between gallium and indium materials, an absorbing GaAs substrate, poor thermal conductivity substrate, and less light output region due to a planar light-emitting surface. These effects will seriously restrict the device performances. Recently, several beneficial methods that could enhance the output light efficiency have been demonstrated as follows: an absorbing substrate of GaAs was replaced with a GaP transparent substrate (TS) via a direct wafer-bonding technique [5]; the truncated inverted pyramid geometry LED method could enhance the lateral light output [6]; a surface textured by the natural lithography method to increase the critical angle and the probability of emitted light escaping from the air–semiconductor interface [7]; a surface deposited a transparent film of CTO (cadmium–tin oxide) or ITO (indium–tin oxide) for enhancing the critical angle and as a function of a current spreading layer [8]; and a novel technique of omni-directional reflector (ODR) structure could enhance light extraction efficiency [9], [10], etc. These solutions have a significant target in common, which is that the photons generated within the LED structure could escape cone after multiple TIR due to the air–semiconductor interface. In this investigation, the absorbing GaAs substrate was replaced with a transparent sapphire substrate by the glue-bonding (GB) technique. This novel structure which has an oblique shaping sidewall could reduce the output light loss caused from many times internal reflection and an absorbing GaAs substrate. The benefit of this oblique shaping sidewall could enhance the total flux, which is a useful contribution towards the lateral output light.

II. EXPERIMENT

In this study, the structure was grown on 2-inch GaAs substrates by a low pressure (50 torr) metal–organic chemical vapor deposition system. The LED structure comprised a 0.1-μm-thick etching stop layer n-$Ga_{0.5}In_{0.5}P$ grown on a 0.3 μm-thick n-GaAs buffer layer, a 4-μm-thick Si-doped n-$(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ layer for surface textured, a 0.7-μm-thick Si-doped n-$Al_{0.5}In_{0.5}P$ cladding layer, a 0.5-μm-thick undoped active layer with 20 period $(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$–$In_{0.5}Ga_{0.5}P$ multiple quantum-wells (MQWs), a 0.7-μm-thick Mg-doped p-$Al_{0.5}In_{0.5}P$ cladding layer, and a 3-μm-thick Mg-doped p-GaP window layer. Finally, a 5-nm-thick p^+-GaP contact layer with heavily doped $(p = 1 \times 10^{-19}\ \mathrm{cm}^{-3})$ grown on the surface for improving ohmic contact formation. Before GB processing, a c-plane sapphire substrate was lapped and polished from 450-μm thickness to 220 μm. Then, a 2-μm-thick SiO_2 with

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1000 μm × 1000 μm was deposited onto the backside sapphire substrate via plasma-enhanced chemical vapor deposition and defined pattern using a standard photolithography as a function of the wet-etching hard mask. The sapphire substrate was then immersed into a $3H_2SO_4 : 1H_3PO_4$ solution at an etching temperature of 340 °C for 40 min. The etching rate of the sapphire substrate is closely achieved 1.4 μm per minute in this study. The etching rate depended on the H_3PO_4 concentration and the temperature of etching solution. Then, a 280-nm-thick ITO film as a function of an ohmic contact layer was deposited on p^+-GaP surface by e-beam evaporation. The epi-wafer was flipped and bonded to a Si substrate with commercially available epoxy glue, and the wafer pair was loaded into a furnace under 300 °C for 40 min in nitrogen ambiance. After the wafer bonding process, the absorbing GaAs substrate and the etching stop layer were removed by chemical etching solution of NH_4OH based and $H_3PO_4 : HC1$, respectively. In the surface roughed textur processes, thin metal layers of Au–AuGe $(300\ \text{Å}/200\ \text{Å})$ were deposited on n-AlGaInP layer surface and alloyed by rapid thermal annealing (RTA) at 450 °C for 1 min in nitrogen ambiance. The dense, strong, and natural particles with nano-scale were clustered on surface to serve as the wet etching mask. The wafer was immerged into chemical solutions of KI and H_3PO_4, respectively. After the etching processes, the n-side-up surface with a nano-roughed texture was taken shape. Then, a regular array of Au–AuGe n-contact micro-dots shaped metal was deposited on the roughed surface. A 280-nm-thick ITO was deposited on the surface as functions of current spreading, transparent conductive layer, and lower reflective index window layer. The GSS-LEDs with a chip size of 1000 μm × 1000 μm were fabricated using standard photolithography processes which were aligned with the backside shaping pattern of a sapphire substrate. The devices mesa etching used an etcher of inductively coupled plasma until the p-side ITO layer was exposed for p-electrode formation. The Ti–Pt–Au (100 nm/50 nm/2500 nm) metals were then deposited for the p- and n-contact pads. Finally, the geometric sapphire shaping wafer was subjected to laser scribed and broken into 1000 μm × 1000 μm chips size in this study. The chip was bonded on ceramic of PLCC 5050 package model for electrical and optical property measurements by CAS140CT-152 array spectra-meter system.

III. RESULTS AND DISCUSSION

A schematic diagram of the AlGaInP-based GSS-LED structure with an oblique sidewall substrate and a sandwich transparent conductive ITO layer is shown in Fig. 1(a). In this study, the oblique sidewall angle of the sapphire substrate depends on the sapphire crystallography. Its crystalline facets were R-plane (1102), M-plane (1010), and A-plane (1120) against the c-axis (0001) and their angles against the c-axis (0001) are about 60°, 50°, and 29°, respectively. Fig. 1(b) illustrates the different extracted light path of the GSS-LEDs and the conventional GB-LEDs. As this schematic diagram results, the GSS-LEDs with more opportunities of output light escaped from the oblique sidewall of the sapphire substrate. Fig. 2(a) and (b) shows the scanning electron micrograph (SEM) images of the 1-mm^2 square GSS-LED devices profile, which has a geometric sapphire shaping. Fig. 2(c) and (d) shows the surface with a nano-roughed texture on the thick n-AlGaInP surface layer via natural cluster metal nano-mask and chemical etching processes. A result of this surface roughed texture depends on the natural cluster metal (Au–AuBe) thickness, RTA temperature and time, and chemical etching solution ratio. Fig. 3(a) and (b) shows the photomicrographs of the GB-LEDs and the GSS-LEDs. These two kinds of device structures replaced the conventional GaAs substrate with a transparent sapphire substrate. In these structures, the radiate output light is not only a surface emitter but a volume emitter. In addition, it is significant that the oblique sidewall of GSS-LEDs (b) appear

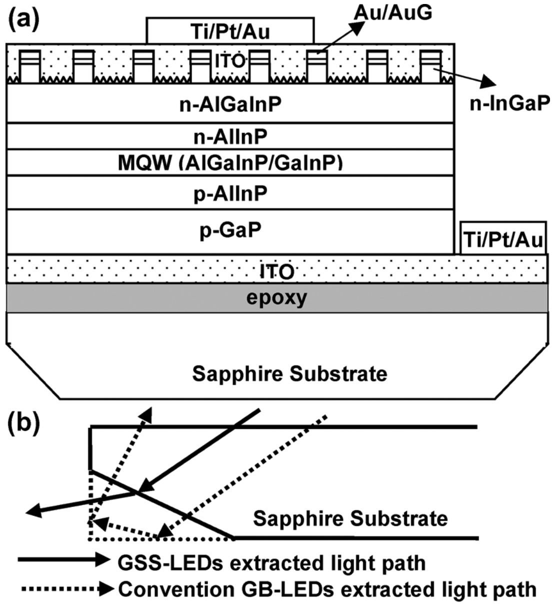

Fig. 1. (a) Schematic diagram of the AlGaInP-based GSS-LED structure with surface textured and sandwich transparent conductive ITO layer. (b) Illustration of the different extracted light paths of the GSS-LEDs and the conventional GB-LEDs.

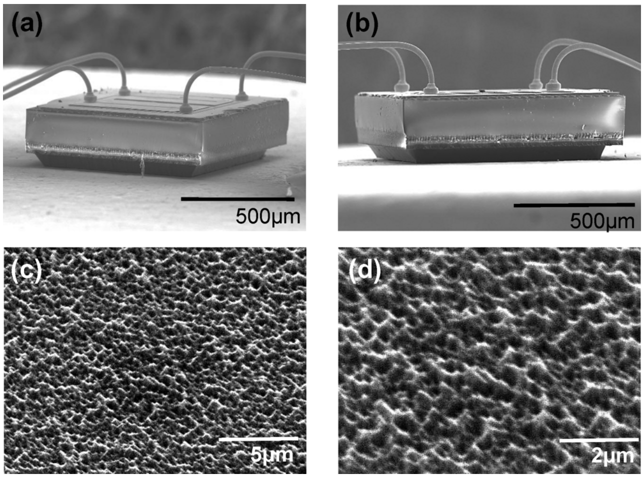

Fig. 2. SEM images of (a), (b) schematic diagram of the AlGaInP-based GSS-LED structure with a surface textured and a sandwich transparent conductive ITO layer. (c), (d) Illustration of the wafer surface with a nano-roughed texture on the thick n-AlGaInP surface layer via natural cluster metal nano-mask and chemical etching processes.

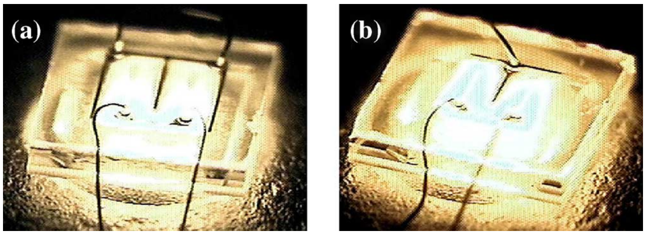

Fig. 3. Tilted cross section photomicrographs view of (a) GB-LED and (b) GSS-LED chip under a forward current 70-mA injection.

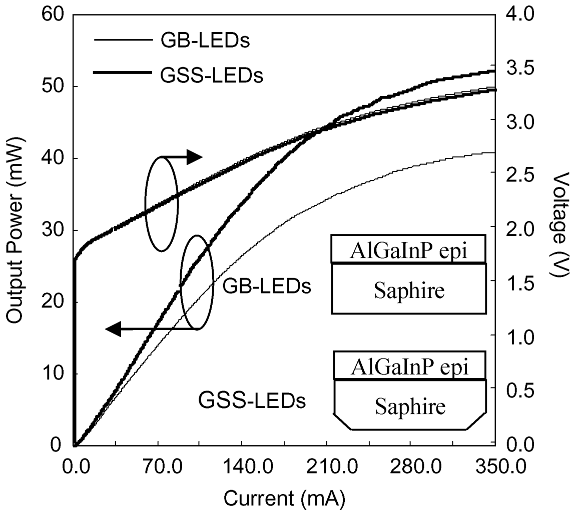

Fig. 4. Corresponding luminous intensity–current–voltage (L–I–V) characteristics of the conventional GB-LEDs and the novel GSS-LEDs.

at a higher brightness under 70-mA current injections as compared with the GB-LEDs (a). As a result, the light extraction efficiency was enhanced via oblique sapphire geometry. The corresponding luminous intensity–current–voltage characteristics of these models were measured, respectively, as shown in Fig. 4. The forward voltage (at 350 mA) of the GB-LEDs and the GSS-LEDs is 3.30 and 3.28 V, respectively. Both of the electrical behaviors are very close and normal. In the luminous intensity versus current result, it is clearly observed that the luminous intensity of the GSS-LEDs is larger than the GB-LEDs. Under 350-mA current injections, the power intensity of the GB-LEDs and the GSS-LEDs is approximately 40.8 and 51.7 mW, respectively. It is found that the luminous intensity of the GSS-LEDs without an epoxy lens encapsulated could be enhanced about 26.7% under 350-mA current injections as compared with the GB-LEDs. It is indicated that the oblique sidewall could reduce the TIR and improve the light extraction probability of photons escaping from semiconductor to air. Fig. 5 shows the normalized output beam pattern of the GB-LED and the GSS-LED samples under 70-mA current injections, respectively. In this compared figure, it is clearly noted that the 50% power angle of the GSS-LEDs is approximately 12.5° wider as compared with the GB-LEDs. It is a fresh indication that the enhancements of the 50% power angle and output power could be attributed to the geometric sapphire shaping LEDs with an oblique sidewall.

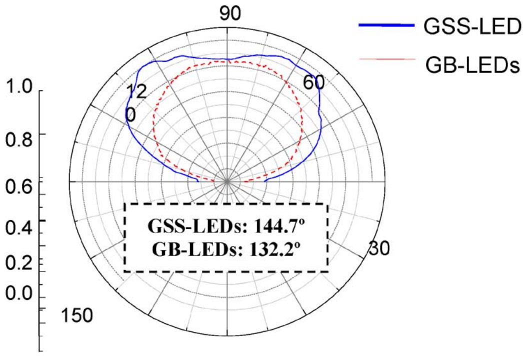

Fig. 5. Beam patterns of the GB-LEDs and GSS-LEDs under 70-mA current injection.

In summary, the GSS-LEDs with an oblique sapphire geometric substrate were fabricated via GB. In these evolutionary GSS-LED performances, the light output power could be enhanced 26.7% under 350-mA current injections. Furthermore, it was demonstrated that the GSS-LED structure could not only reduce the TIR effect but increase more probabilities of output light escaping from the TS with an oblique sidewall.

REFERENCES

[1] C. P. Kuo, R. Fletcher, T. Osentowski, M. Lardizabal, M. Craford, and V. Robbins, "High performance AlGaInP visible light-emitting diodes," *Appl. Phys. Lett.*, vol. 57, no. 27, pp. 2937–2939, Dec. 31, 1990.

[2] H. Sugawara, M. Ishikawa, and G. Hatakoshi, "High-efficiency InGaAIP/GaAs visible light-emitting diodes," *Appl. Phys. Lett.*, vol. 58, pp. 157–160, 1991.

[3] K. Kobayashi, "Room-temperature CW operation of AlGaInP double hetero-structure visible lasers," *Electron. Lett.*, vol. 21, pp. 931–932, 1985.

[4] P. Altieri, D. Eisert, A. Jaeger, R. Windisch, N. Linder, P. Stauss, R. Oberschmid, and K. Streubel, "Analysis of internal quantum efficiency of high-brightness AlGaInP LEDs," in *Proc. 4th Int. Conf. Numerical Simulation Optoelectronic Devices*, Santa Barbara, CA, 2004, pp. 13–14.

[5] F. A. Kish, F. M. Steranka, D. C. DeFevere, D. A. Vanderwater, K. G. Park, C. P. Kuo, T. D. Osentowski, M. J. Peanasky, J. G. Yu, R. M. Fletcher, D. A. Steigerwald, M. G. Craford, and V. M. Robbins, "Very high-efficiency semiconductor wafer bonded transparent substrate $(\mathrm{Al}_x\mathrm{Ga}_{1-x})_{0.5}\mathrm{In}_{0.5}$P/GaP light-emitting diodes," *Appl. Phys. Lett.*, vol. 64, pp. 2839–2841, 1994.

[6] M. R. Krames, M. Ochiai-Holcomb, G. E. Höfler, C. Carter-Coman, E. I. Chen, I.-H. Tan, P. Grillot, N. F. Gardner, H. C. Chui, J.-W. Huang, S. A. Stockman, F. A. Kish, M. G. Craford, T. S. Tan, C. P. Kocot, M. Hueschen, J. Posselt, B. Loh, G. Sasser, and D. Collins, "High-power truncated inverted pyramid $(\mathrm{Al}_x\mathrm{Ga}_{1-x})_{0.5}\mathrm{In}_{0.5}$P/GaP light-emitting diodes exhibiting $>50\%$ external quantum efficiency," *Appl. Phys. Lett.*, vol. 75, pp. 2365–2367, 1999.

[7] R. Windisch, B. Dutta, M. Kuijk, A. Knobloch, S. Meinlschmidt, S. Schoberth, P. Kiesel, G. Borghs, G. H. Döhler, and P. Heremans, "40% efficient thin-film surface-textured light-emitting diodes by optimization of natural lithography," *IEEE Trans. Electron Devices*, vol. 47, no. 7, pp. 1492–1498, Jul. 2000.

[8] D. J. Lawrence, D. C. Abbas, D. J. Phelps, and F. T. J. Smith, "$\mathrm{GaAs}_{0.6}\mathrm{P}_{0.4}$ LED's with efficient transparent contacts for spatially uniform light emission," *IEEE Trans. Electron Devices*, vol. ED-30, no. 6, pp. 580–585, Jun. 1983.

[9] T. Gessmann, E. F. Schubert, J. W. Graff, K. Streubel, and C. Karnutsch, "Omnidirectional reflective contacts for light-emitting diodes," *IEEE Electron Device Lett.*, vol. 24, no. 11, pp. 683–685, Nov. 2003.

[10] T. Gessmann, H. Luo, J. Q. Xi, K. P. Streubel, and E. F. Schubert, "Light-emitting diodes with integrated omnidirectionally reflective contacts," in *Proc. SPIE Int. Soc. Opt. Eng.*, 2004, vol. 5366, pp. 53–61.