JOURNAL OF THE
ELECTRON DEVICES SOCIETY

Received 2 March, 2018; accepted 4 April, 2018. Date of publication 6 April 2018; date of current version 19 April 2018.
The review of this paper was arranged by Editor A. Nathan.

Digital Object Identifier 10.1109/JEDS.2018.2823981

Development and Fabrication of AlGaInP-Based Flip-Chip Micro-LEDs

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This work was supported in part by the Ministry of Science and Technology, Taiwan under Grant MOST 105-2221-E-009-183-MY3 and Grant 104-2221-E-009-119-MY3, and in part by the South Science Park and Hsinchu Science Park under Contract 105CE01 and Contract 106A03, respectively.

ABSTRACT The fabrication of AlGaInP-based flip-chip micro light-emitting-diodes (LED; emitting area: 4.5 mil × 5 mil) with horizontal electrodes is reported in this paper. The thickness of the epitaxial layer of the thin LED structure was reduced to 50% of that of the traditional thick LED, whereas carrier concentration in the n-type GaAs contact layer was increased to 5×10^{18} cm^{-3} to meet the Ohmic contact requirement. At a current injection of 5 mA, the thin LED exhibited a forward voltage, output power, and external quantum efficiency of 1.8 V, 1.9 mW, and 19%, respectively. The optoelectronic performance of the thin LED was as good as that of the traditional thick red LED. The technique proposed by this paper can be used to integrate AlGaInP-based LEDs with nitride LEDs for full-color display applications.

INDEX TERMS Flip-chip, light-emitting diodes, micro-LED.

I. INTRODUCTION

Light-emitting diodes (LEDs) are highly popular solid-state self-emissive devices. The intrinsic physical characteristics of LEDs allow their operation at low voltages/currents with high efficiency, reliability, and long lifetimes. Moreover, LEDs can be operated under extreme conditions, such as extremely high or low temperatures. Therefore, LEDs have extensive applications, such as indoor/outdoor illumination, automotive lighting, traffic signals, and displays. The applications of red-light LEDs are highly mature given their years of extensive development. High-quality red LEDs based on $(\mathrm{Al_xGa_{1-x}})_{0.5}\mathrm{In_{0.5}P}$ and with internal quantum efficiencies exceeding 90% can be grown on precisely lattice-matched GaAs substrate by metalorganic chemical vapor deposition (MOCVD) without the generation of excess dislocations [1]–[4]. Nevertheless, GaAs is a light-absorbing material for AlGaInP LEDs, thus limiting the light extraction performances of red and yellow LEDs [5]. Numerous studies have been performed to fabricate the high-brightness thin film LEDs by wafer bonding technology [6], [7], in which light-absorbing GaAs substrate can be removed to improve the efficiency of the LED.

MicroLED (μLED) arrays have emerged as a promising technology with potential applications in self-emissive microdisplays, automobiles, wearable devices, military applications, biological transducers, optical biological chips, and medical treatment. Studies on the development of efficient LEDs within the last decade have focused on the possibility of using III-N semiconductor materials to produce microdisplays as first proposed by Jiang *et al.* in 2001 [8]. Full-color displays that integrate red, green, and blue LEDs are a current development trend. Traditional methods for fabricating μLED arrays involve arranging individual red, blue, and green microchips onto a single substrate. However, the integration of these three kinds of LEDs on one substrate is hindered by fact that p and n electrodes are lateral for green and blue LEDs, whereas they are vertical electrodes for red LEDs. In general, the epilayer thickness of AlGaInP-based LED is approximately 7 μm, thus resulting in a considerable gap between the n and p electrodes [9], [10], as shown in Fig. 1. Moreover, LEDs applied in high-resolution displays should have die sizes of approximately 4 mil. However, decreasing the gaps between the n and p electrodes to shrink die sizes might cause the electrodes to short circuit.

Therefore, in this study, a flip-chip LED on an AlGaInP base (5 mil × 8 mil) with horizontal electrodes was fabricated. Epilayer thickness was decreased from 6.48 µm to 3.6 µm. The optoelectronic performance of the LED was characterized and compared with that of the traditional red LED. The proposed technique can be used to integrate AlGaInP-based LEDs with nitride LEDs for full-color display applications.

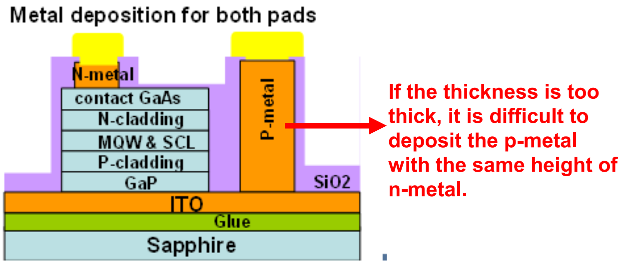


FIGURE 1. Schematic of the thick AlGaInP-based LEDs for difficult lateral electrodes structure.

II. DEVICE FABRICATION

AlGaInP-based LED epilayers were grown on n-type lattice-matched GaAs substrates by MOCVD. The epistructure consisted of a GaInP etching stop layer, n^+-GaAs contact layer, n-cladding AlGaInP, n-type AlInP, separate confinement layer (SCL), GaInP–AlGaInP multiple quantum wells (MQWs), p-type AlInP, p-cladding AlGaInP, a p-GaP:Mg window layer, and carbon-doped p^+-GaP Ohmic contact layer. To fabricate the flip-chip device, an ITO layer was first deposited on the p-type GaP layer using an E-Gun evaporator for Ohmic contact and current spreading. Secondly, glue was used to bond the epilayer-deposited ITO on double-sides polished sapphire substrate (Fig. 2(a)). Following, the GaAs substrate was removed using wet etching (Fig. 2(b)). Next, the n-metal was deposited on the surface of the exposed n^+GaAs layer. Afterward, the n-mesa region was defined by dry etching (Fig. 2(c)). Then, a thick layer of passivated SiO2 was deposited by PECVD to protect the mesa. Moreover, the thick SiO_2 also had a planarization function that decreased the great gap between the n- and p-metal pads. The p-metal Ti/Al/Ti/Au was deposited using the E-Gun evaporator at a thickness of approximately 3.6 µm (Fig. 2(e)). Finally, the n- and p-electrode regions were redefined, and Ti/Au metal was deposited on both n and p electrodes using the E-gun system (Fig. 2(f)).

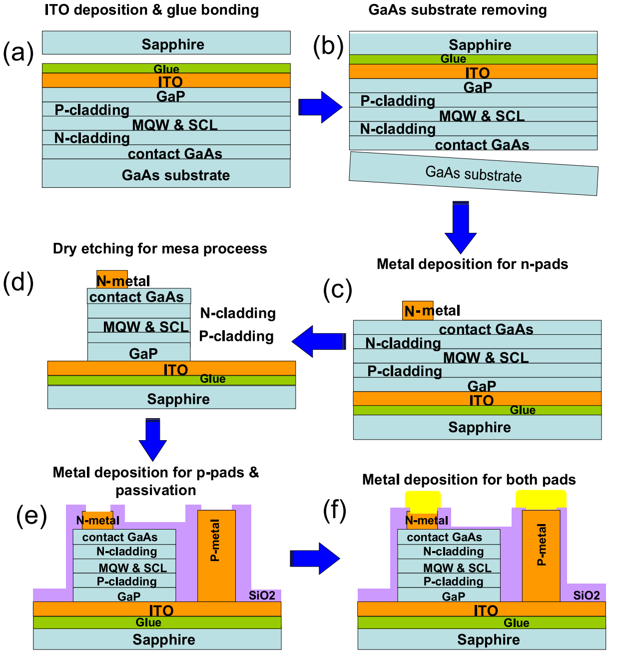
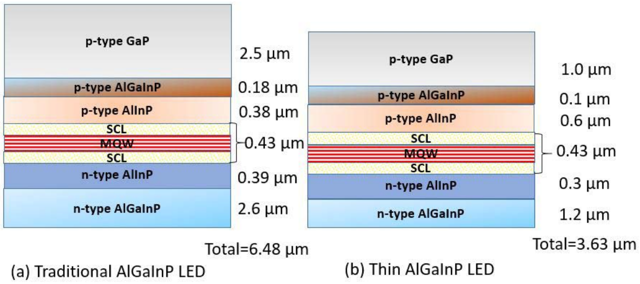


FIGURE 2. Fabrication process of flip-chip LED (a) ITO deposition and Glue Bonding (b) GaAs substrate removing (c) Metal deposition for n-pads (d) Mesa formation by etching process (e) Metal deposition for p-pads and Passivation (f) Metal deposition for both pads.

III. RESULTS AND DISCUSSION

The traditional red LED epi-structure consisted of 2.6 µm-thick n-type AlGaInP, 0.39 µm-thick n-type AlInP, 0.43 µm-thick MQWs and SCL, 0.38 µm-thick p-type AlInP, 0.18 µm-thick p-type AlGaInP, and 2.5 µm-thick p-type GaP window layer. By contrast, the thin red LED epistructure consisted of 1.2 µm-thick n-type AlGaInP, 0.3 µm-thick n-type AlInP, 0.43 µm-thick MQW and SCL, 0.6 µm-thick p-type AlInP, 0.1 µm-thick p-type AlGaInP, and 1 µm-thick p-type GaP window layer. Total thickness decreased from 6.48 µm for the thick LED to 3.63 µm for the thin LED. Nevertheless, LED performance is the most crucial aspect of practical LED applications. The optoelectronic properties of LEDs are dominated by MQW pairs [11]. In this study, the quantum wells have been optimized for the internal quantum efficiency (it is only 10 pairs with 0.18 mm thickness). These pairs can be operated under the low current injection. Moreover, the thickness of MQW is only 0.18 mm. Engineering quantum wells to achieve better optical characteristic is important, but it can not obviously contribute to reduce overall LED thickness. Thus, the MQW pairs that we utilized in the thin LED were the same as those in the traditional thick LED in order to ensure that LED characteristics were not degraded during epitaxial growth. The schematics of the epilayer components of AlGaInP for thick and thin LEDs are depicted in Fig. 3.



(a) Traditional AlGaInP LED (b) Thin AlGaInP LED

FIGURE 3. Schematic of thick and thin epilayers of AlGaInP-based LEDs.

Fig. 4 (a) and (c) show the TEM images of the thick and thin LEDs, respectively. TEM images of the MQW pairs for the thick and thin LED structures are shown in Figs. 4 (b) and (d), respectively. In this study, the thin LED was fabricated by decreasing the thicknesses of the Mg-doped p-GaP window and Si-doped n-AlGaInP layers. The doping concentration of Mg was doubled to keep the carrier concentration of the thin LED equal to that of the thick LED.

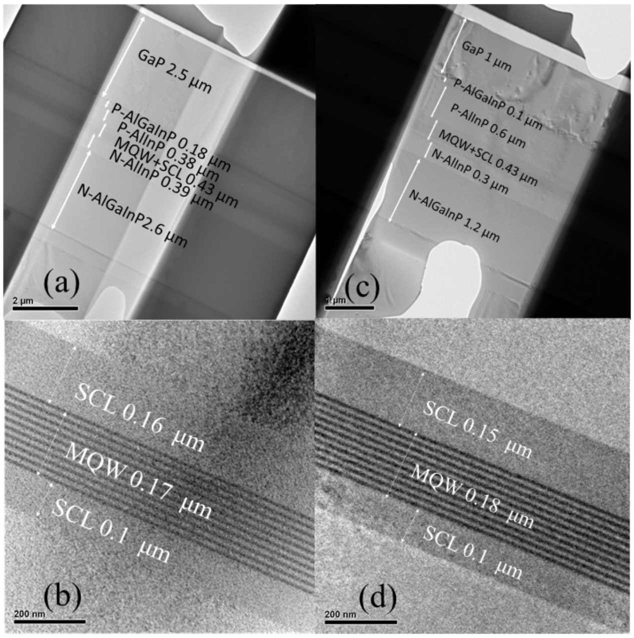


FIGURE 4. **TEM images of the (a) thick epilayer, (b) MQW of the thick epilayer, (c) thin epilayer, and (d) MQW of the thin epilayer.**

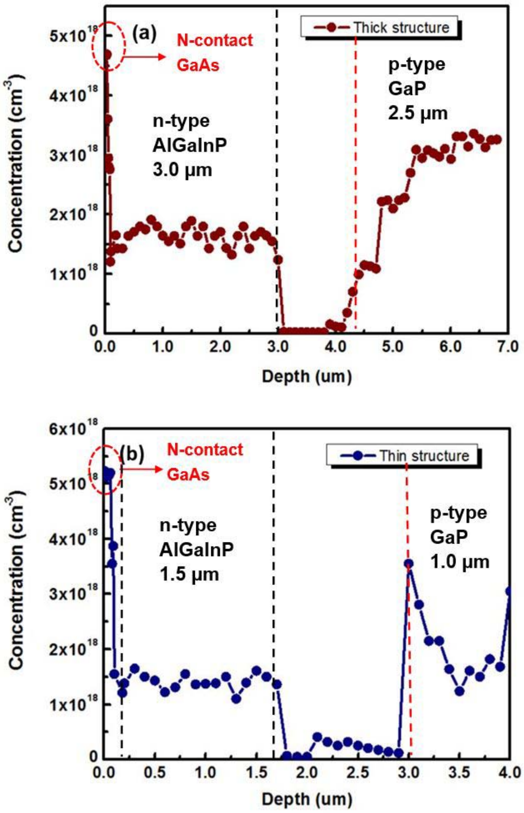


FIGURE 5. **ECV measurement of the carrier concentration of the (a) traditional thick and (b) thin epilayers.**

The carrier concentration of each layer was measured through electrochemical ECV profiling. The ECV measurements for the thick and thin LEDs are shown in Figs. 5(a), and Fig. 5(b), respectively. The images show that carrier concentrations did not significantly decrease although the epilayer thickness of the thin LED had decreased. Compared with that of the thick LED, the carrier concentration of the n+ GaAs layer of the thin LED increased from 4.8×10^{18} cm^{-3} to 5.2×10^{18} cm^{-3}, and the carrier concentration of the p-type layer was maintained at 2×10^{18} cm^{-3}, as shown in Fig. 5.

The contact behaviors of AuGe/Au and n+-GaAs before and after thermal treatment at various temperatures are shown in Fig. 6. It was found that the temperature for the Ohmic contact of the thick LED was 320 °C, whereas that of the thin LED was 300 °C due to the higher concentration of n+-GaAs carriers in the thin LED relative to those in the thick LED. The specific contact resistivity of the thick (@ 320 °C annealing) and thin LEDs (@ 300 °C annealing) as measured through the circular transmission line model (CTLM) were 5×10^{-4} Ω·cm^2 and 1.73×10^{-4} Ω·cm^2, respectively. It is worthy to mention that the contact resistance decrease by three times in thin LEDs compared to thick LED although there is only ∼ 10% concentration increasing in the thin LED (5.2×10^{18} cm^{-3}) greater than the thick LED (4.8×10^{18} cm^{-3}). It could be due to thermal annealing temperature being different, which effects on the interface between metal and semiconductor and sheet resistance measured by the TCLM measurement. The obtained result suggests that high carrier concentration and low annealing temperature would benefit to low specific contact resistance.

The I–V curves of the thick and thin LEDs are shown in Fig. 7. Both LEDs had a forward voltage of 1.8 V. The series resistance of the thick and thin LEDs was 9.02 Ω and 8.02 Ω, respectively. The lower series resistance of the thin LED relative to that of the thick LED may be resulted from the thinner epilayer thickness and the higher n+-GaAs doping concentration for the thin LED. The emission spectra of both LEDs were shown in the insect of Fig. 7. It was found that the peak wavelengths are 627 and 632 nm for the thick and thin film LEDs, respectively. Although the composition of AlGaInP epilayers in the LED structures is lattice matched to GaAs substrate, there exists the stress due to the different thermal expansion coefficiency between AlGaInP epilayers and GaAs substrate. The thickness of epilayers will affect the emission wavelength, even the MQW is the same. As concerning the emission wavelength, it should be finely tuned according the epilayer thickness.

The measured output power and external quantum efficiency (EQE) are shown in Fig. 8. At the current injection

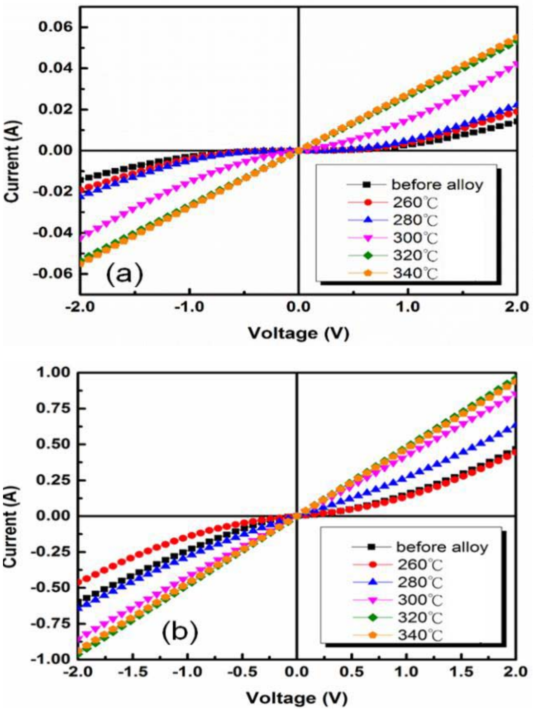


FIGURE 6. I–V curves of n + GaAs and AuGe/Au layers annealed at different temperatures; (a) traditional thick epilayer and (b) thin epilayer.

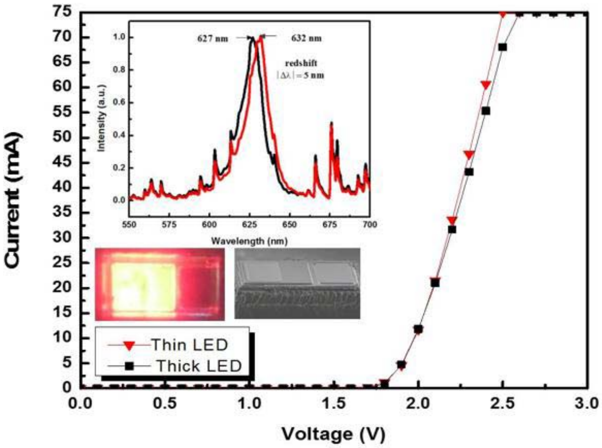


FIGURE 7. I–V curves of thick and thin LEDs.

of 5 mA, the output power and EQE of the thin LED were 1.9 mW and 19%, respectively, whereas that of the thick LED were 1.5 mW and 17%, respectively. The output power and EQE of the thin LED were higher than those of the thick LED by 26.6% and 11.8%, respectively, given that the total thickness of the thin LED was lower than that of the thick LED. However, as the current injection was increased to 45 mA, the output power and EQE of the thin LED decreased to 4.5 mW and 5.1%, respectively, whereas those of the thick LED decreased to 5 mW and 5.7%, respectively. The thick LED exhibited better photoelectric characteristics than the thin LED when current injection exceeded 45 mA. This characteristic could result from the premature peaking of the current to the thinning of the n-cladding layer in the thin LED. The ITO/GaP layer was applied as a current spreading layer for both kinds of red LEDs [12]–[15]. Thus, spreading worsened with increasing current injection given that the thickness of the GaP layer drastically decreased in the thin LED. Nevertheless, the thin LED is still suitable for μLED display applications because the operating current of μLEDs is considerably lower than that of traditional LEDs.

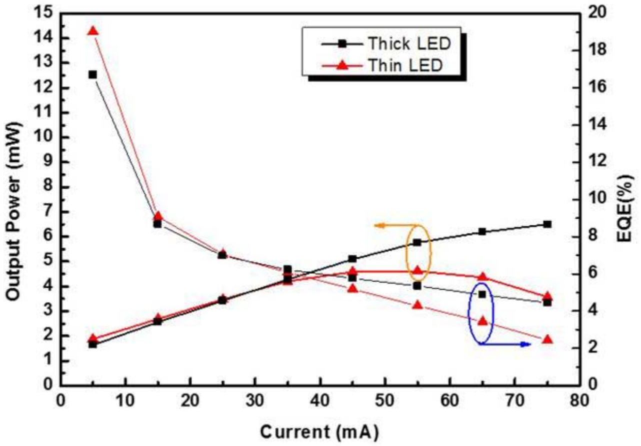


FIGURE 8. Output power and external quantum efficiency (EQE) as functions of the current of LEDs with thick or thin epilayers.

IV. CONCLUSION

A flip-chip red LED with a thin epitaxial layer and horizontal electrode was fabricated. TEM revealed that the thickness of the thin LED decreased from 6.48 μm to 3.6 μm, whereas the values of its MQW pair and thickness remained equal to those of the traditional thick LED (6.48 μm). ECV measurements showed that the carrier concentration of the thin LED did not significantly change. The specific contact resistivity of the thin LED was lower (1.73 × 10^{-}4 Ω·cm^{2}) than that of the traditional thick LED (5 × 10^{-4} Ω·cm^{2}). Moreover, IV measurement revealed that the annealing temperature of the n^{+}GaAs and AuGe/Au for Ohmic contact decreased to 300 °C. The forward voltage, output power, and EQE of the thin LED under 5 mA injection current were 1.8 V, 1.9 mW, and 19%, respectively. The advantages of flip chips, such as large luminous region, excellent heat dissipation, and wireless bonding, were emphasized through the proposed method. The proposed method can be used to integrate AlGaInP-based LEDs with nitride LEDs for applications in full-color displays.

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