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Light Extraction Enhancement of Wafer-Bonded AlGaInP-Based Light-Emitting Diodes with Micro- and Nano-Scale patterned Surface

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1. Introduction

Recently, the high efficiency light-emitting diodes (LEDs) of AlGaInP-based quaternary materials with a visible spectrum from red to yellow-green were widely applied for many applications such as optical communications light source, full-color display, traffic signal, automotive exterior lighting, indoor and outdoor display, decorative lighting, etc [1], [2]. The LEDs efficiencies are depended on the internal quantum efficiency (η_i) and external quantum efficiency (η_{ext}). Recent years, the epitaxy technique on the AlGaInP materials was greatly improved and the internal quantum efficiency had already approached to 90% or higher [3] due to the excellent epitaxy technique. However, the external quantum efficiency is limited owing to the absorbing GaAs substrate and large reflection index different between the AlGaInP-based material and outside medium such as air or epoxy. Many investigations have been implemented for enhancing light extraction efficiency in AlGaInP LEDs structure. In this investigation, the absorbing GaAs substrate was also replaced by a high thermal dispersion Si substrate, and then micro-bowls array and nano-rods surface textured processes were implemented, which are created using nano-particle spin coating, dry- and wet-etching techniques. Detailed experiment steps, device structure, performances and results will be illustrated in subsequence paragraphs.

2. Experiment and Discussion

In this study, the AlGaInP LEDs structure was epitaxially grown on 2-inch GaAs (100) substrates by a low pressure metal-organic chemical vapor deposition (MOCVD) system. This structure with a dominant wavelength (λ_d) at 625 nm comprised a 0.1 μm-thick n-Ga0.5In0.5P etching stop layer grown on a GaAs buffer layer, a 2 μm-thick Si doped n-(Al0.5Ga0.5)0.5In0.5P, a 0.5 μm-thick Si doped n-Al0.5In0.5P cladding layer, a 0.5 μm-thick unintentionally doped active layer with 20 periods (AlxGa1-x)0.5In0.5P/ (AlyGa1-y)0.5In0.5P multiple quantum wells (MQWs), a 0.8 μm-thick Mg doped p-Al0.5In0.5P cladding layer, a 5 μm-thick Mg doped p-GaP window layer. Finally, an 8 μm-thick double window layer with an ultra-thin GaAs layer was inserted between the p-GaP surface window layer and p-Al0.5In0.5P cladding layer [4]. Before the metal bonding process, the AuBe/ Au metal dots were arraying contacted on the p-GaP surface as a function of p-type ohmic contact. A SiO2 layer, which the thickness is equal to the AuBe / Au metal was selectively deposited on the p-GaP window layer. A quarter-wave thick indium-tin-oxide (ITO) was sequentially deposited. Next, a 300 nm silver layer was deposited on the ITO layer to achieve the GaP- SiO2-ITO-Ag omni-directional reflector (ODR) design in order to enhance the reflectivity. Besides, the Ti/ W/ Pt/ Au multi-layer were orderly stacked on Ag layer to serve a function of adhesion, barrier, and bonding metal. The surfaces of p-type Si substrate were successively deposited Ti/ Au/ In metal for ohmic contact and bonding material. The epi-wafer was flipped and bonded to the Si substrate in 220°C ambience. The absorbing GaAs substrate and the etching stop layer were removed by ammonia- and phosphoric-based chemical etchant after metal bonding process. The AuGe alloy metal for n-type contact was deposited on the n-(Al0.5Ga0.5)0.5In0.5P surface layer. In this study, there are three different surface types of LED-I, LED-II, and LED-III. The surface profile in LED-I devices is plane and without any surface textured. The micro-scale surface textures having periodic arrangement were applied to LED-II surface for enhancing light extraction efficiency. The micro-scale surface textures were produced on 2 μm-thick n-AlGaInP layer using photolithography and wet-etching process. The LED-II wafers were immersed in chemical mixture solution of bromine and acetic acid for half minute. And then make sure the etched area was appeared bowl-shaped and its maximum depth was closely 1.2 μm. Each mask dot dimension and distance is 3 μm after photolithograph definition, and the 5 μm wide bowl-shaped texture was created after anisotropic etching process. The last type is LED-III, having micro- and nano-scale texture on surface and was produced using twice surface roughness process.

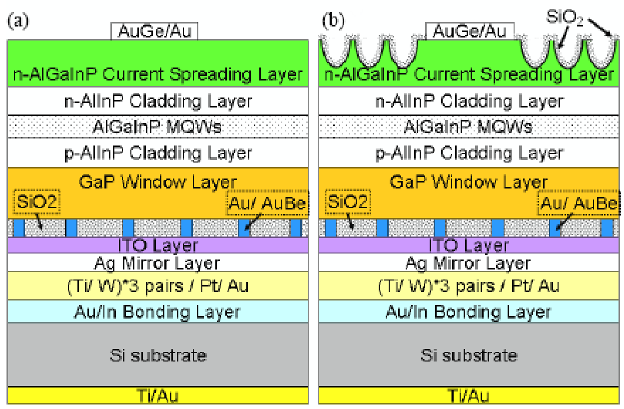

Fig. 1. Schematic diagram of the metal bonding AlGaInP-based LEDs (a) The LED-I device structure has a plane surface. (b) The LED-II device has micro-bowls array texture on surface and the LED-III device is added nano-rods texture in micro-bowls.

3. Results and discussion

A schematic diagram of three different type (LED-I, LED-II, and LED-III) metal bonding AlGaInP-based LEDs were shown in Fig. 1, illustrating the devices structure and surface profile. Fig. 1(a) shows the LED-I device structure, having a plane surface. The surface with micro-bowls shape texture (LED-II) and added nano-rods texture covered in micro-bowls (LED-III) were shown in Fig. 1(b). The schematic diagram of the silica nano-particles were spin-coated on the wafer surface which were covered through micro-bowls on surface as shown in Fig. 2(a). After dry-etching and the nano-masks were removed, the nano-rods were formed in micro-bowls surface.

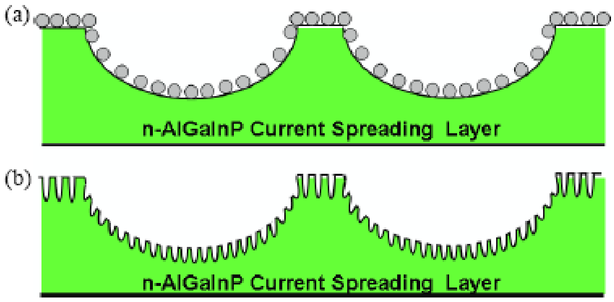

Fig. 2. Schematic diagram of (a) The silica nano-particles were spin-coated on the wafer surface which has bowl-shaped textured. (b) The nano-scale rod was formed on surface after dry-etching process.

Fig.3 (a) shows the SEM image of the micro-bowls shaped array texture on LED-II wafer surface, and each micro-bowl dimension of width and depth is 5 μm and 1.2 μm, respectively. The silica nano-particles were spin-coated on wafer surface and each sphere diameter is 120 nm as shown in Fig. 3(b). Fig. 3 (c) (d) shows the nano-rods were formed through the surface including bowl bottom, bowl sidewall, and plane surface.

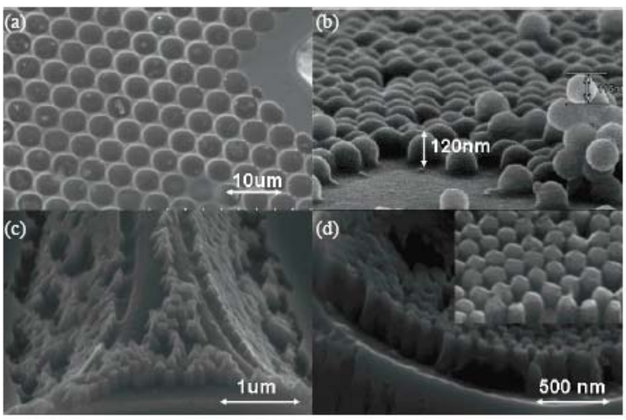

Fig. 3. The SEM figures of (a) The micro-bowls array texture on LED-II surface. (b) The silica nano-particles were spin-coated on surface. (c) and (d) The nano-rods were formed through wafer surface including bowl bottom, bowl sidewall, and plane surface.

Fig. 4 shows the plane surface devices (LED-I), micro-bowls textured surface devices (LED-II), and nano-rods were added in micro-bowls textured surface devices (LED-III) performances of forward voltage and luminous intensity versus injection current. With a injection current of 20-mA, the forward voltage of these three types LEDs are almost approximate 1.95 V, and luminous intensity of LED-I, LED-II, and LED-III is 240, 337, and 397 mcd, respectively. Comparing LED-I to LED-II at 20-mA, 40.8% enhancement of luminous intensity was observed and 65.8% luminous intensity enhancement of comparing LED-I to LED-III. The LED-III exhibits highest luminous intensity, in other words, the LED-III has highest light output on off-axis. Furthermore, added nano-rods textured in micro-bowls textured can enhance 17.7% due to the micro- and nano-scale surface texture conduces the less total internal reflection effect.

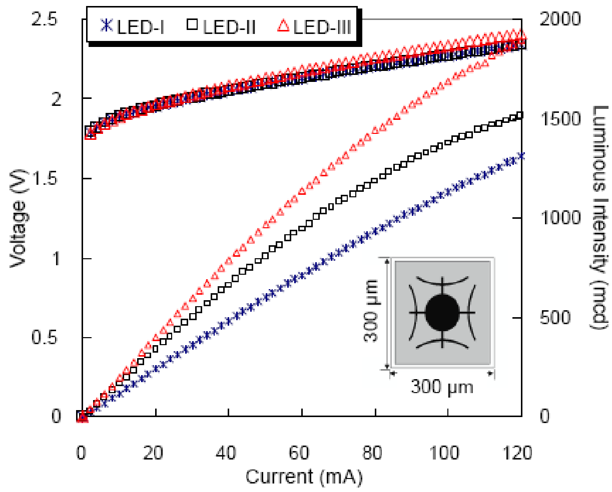

Fig. 4. The corresponding luminous intensity-current-voltage (L-I-V) characteristics of the LED-I, LED-II, and LED-III.

4. Conclusions

In summary, a high light extraction efficiency metal-bonding AlGaInP-based LED has been fabricated using micro- and nano-scale surface textured process. This novel LED-III structure surface was covered with the periodical micro-bowls in which the random nano-rods were added. In this evolutional LED-III performances, the light output power could be 65.8% under 20-mA current injection as compared with the plane surface device of LED-I.

Acknowledgements

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