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Improving the External Quantum Efficiency of High Power GaN Based Flip-Chip LEDs using Ag/SiO₂/DBR/SiO₂ Composite Reflective Structure

Liang Xu¹, Jinglin Zhan², Huiqing Sun¹, Zhizhong Chen² and Zhiyou Guo¹

Improve the light extraction efficiency and light output in the vertical direction of LEDs for high-power applications, flip-chip LEDs (FCLEDs) with an Ag/SiO₂/distributed Bragg reflector/SiO₂ composite reflection structure (CRS) were fabricated. The enhanced opto-electrical properties were thoroughly investigated. Compared with the normal Ag-based FCLEDs, the light output power of the CRS-FCLEDs is increased by 6.3% at an operational current of 1500 mA, with the corresponding external quantum efficiency improved by 6.0%. Further investigation proved that the CRS structure exhibited higher reflectance compared with the commonly used Ag-mirror reflective structure, which originates from the increased reflective area in the sidewall and partial area of the n-GaN contact holes. Moreover, the light emission intensity distributions and far-field angular light emission measurements show that the CRS-FCLED has a strengthened light output in the vertical direction, which shows great potential for applications in high-power fields, such as headlamps for automobiles.

With the development of semiconductor materials and packaging technology, the luminous flux of high-power white LEDs has rapidly improved. The application of LEDs in the automotive lighting field has gradually expanded, from signal indicators to current automotive headlights, reflecting the development trend that LEDs will become the mainstream light source in this field ^{[1]-[4]}.

Flip-chip LEDs (FCLEDs) exhibit excellent heat dissipation performance and high light efficiency and have been attracting great attention in the field of high-power LEDs. Forming a p-type ohmic contact electrode with high reflectance and low ohmic contact resistance is the key to realize high-efficiency FCLEDs ^{[5]-[7]}. However, in the high power LED lighting market, automobile headlights, and searchlights require high current density and LED light extraction efficiency ^{[8]-[10]}. Meanwhile, automotive headlights are used in an array of dense packaging, requiring a higher LED vertical light efficiency ^[11]. Ag-based reflective p-electrodes are widely used in FCLEDs owing to their superior electrical properties and high reflectivity in the visible wavelength range ^[12]. However, the Ag contact suffers from poor adhesion, inferior ohmic behavior, and thermal instability such as migration. Therefore, it is necessary to maintain a sufficient distance between the Ag mirror and a PN junction in the LED chip design, and cover it with a TiW barrier diffusion layer ^{[13], [14]}, resulting in the loss of emission area and thus reducing the output efficiency. In addition to the normal Ag-base FC LED device structures, there are also DBR-base FC LED

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device structure which use ITO and interdigitated metal contact for current spreading layers., but these structures bring out degradation of the optical performance, reliability. and lifetime of the optoelectronic device with the high power input due to the poor current spreading ability of the interdigitated metal contact ^{[15]-[17]}.

In this paper, we report the demonstration of an FCLED with a novel composite reflection structure (CRS-FCLED) that simultaneously improves the light output power (LOP) and vertical light extraction efficiency. Compared with the commonly used FCLED with a single Ag-mirror layer as the reflective layer, the CRS-FCLED with an Ag/SiO₂/distributed Bragg reflector (DBR)/SiO₂ reflective structure exhibited improved reflectance. Further investigation proved that the SiO₂/DBR/SiO₂ composite layer covers the sidewall and part of the area of the n-GaN contact holes that are evenly distributed across the whole area of the LED chips, which improves the light extraction efficiency. When operated under currents of 700, 1000, and 1500 mA, the light outputs of the CRS-FCLEDs are improved by 3.8, 5.1, and 6.3%, respectively, and the corresponding external quantum efficiencies (EQEs) improved by 3.4, 4.7, and 6.0%, respectively. Moreover, the light emission intensity distributions and far-field angular light emission measurements proved that the CRS-FCLED can strengthen the light output in the vertical direction, which is advantageous for high-power field applications, such as headlamps for automobiles.

Results

The LED samples were grown on the c-plane of the patterned sapphire substrate using the metal–organic chemical vapor deposition (MOCVD) method. The epitaxial structures of the LED from the bottom to the top consist of an AlN buffer layer with a thickness of 20 nm, a 3- μm undoped GaN layer, a heavily Si high doping n-GaN layer with a thickness of 2.5 μm , an InGaN/GaN superlattice structure with a thickness of 120 nm that can act as a strain release layer, five pairs of InGaN/GaN multiple quantum wells (MQWs) with a thickness of 30 nm, a 40-nm low temperature p-GaN layer, a 48-nm p-AlGaIn/GaN electron blocking layer, and a 110-nm Mg- doped p-GaN layer. The dimensions of the CRS-FCLED are $1400 \times 1400 \mu\text{m}^2$ for high-power applications.

Fig. 1. Main fabrication process of the CRS-FCLED.

The main fabrication processes of the CRS-FCLED are shown in Fig. 1. The detailed processing steps are as follows:

the n-GaN contact holes are fabricated by an inductively coupled plasma (ICP) etching method with a BCl_3/Cl_2 mixture gas. A 10-nm ITO contact layer was then deposited on the p-GaN by the magnetron sputtering method, followed by annealing in N_2 ambient at 550 °C to improve the contact properties. Subsequently, a layer of Ag (120 nm) is sputtered on top of the ITO that acts as the reflecting layer [Fig. 1(a)]. For the fabrication of the CRS structure, a layer of SiO_2 (300 nm) was first deposited on top of the Ag-mirror layer, after which an insulating DBR structure with 20 pairs of periodically arranged SiO_2 and TiO_2 layers (82.3 nm/40.5 nm) is deposited on the top of the SiO_2 layer and partially filled the via holes. Then, a 300-nm SiO_2 layer is deposited on top of the DBR structure for better passivation protection. Finally, the p-GaN contact holes and n-GaN contact holes were fabricated by ICP etching with a CF_4/O_2 gas mixture as the etching gas source [Fig. 1(b)]. After the fabrication of the CRS structure, the first electrode layers of Cr (0.5 nm)/Al (1 μm)/Cr (40 nm)/Pt (0.2 μm) were deposited on the DBR and filled the p-contact hole and n-contact holes. A SiO_2 insulating layer with a thickness of 1.2 μm is deposited on the top of the first electrode layer grown by plasma-enhanced chemical vapor deposition, with the interconnected holes formed by the buffer oxide etchant (BOE) wet etching method. Finally, an AuSn alloy solder layer was deposited by thermal evaporation to meet the welding reliability requirements for headlamp applications [Fig. 1(c)].

The p-type ohmic contact electrodes of FCLEDs should have high reflectivity and low contact resistance. To realize this, metallic and DBR mirrors can be used as highly reflective layers in flip chips owing to their high reflectance in the visible wavelength range [18]. Further, ITO was sandwiched between the reflection layer and the p-GaN to decrease the p-type contact resistance. on the other hand, DBR instead of metallic mirrors as the same reflective properties [19]. For comparing the reflectance, Ni (0.1 nm)/Ag (150 nm), ITO (10 nm)/Ag (150 nm), ITO (10 nm)/ DBR (2.1 μm), and ITO (10 nm)/ Ag (150 nm)/ SiO_2 (300 nm)/ DBR (2.1 μm) / SiO_2 (300 nm) films were deposited on the quartz glass. To simulate the actual reflection of the chip, all the layers are patterned by a photoresist mask and etched by ICP etching with a CF_4/O_2 gas mixture. The reflectance as a function of wavelength is shown in Fig 2.

Fig. 2. Reflectances of Ni/Ag, ITO/Ag, and ITO/CRS films

At the wavelength of 450 nm, the measured reflectances of Ni/Ag, ITO/Ag, and ITO/CRS are 93.3%, 96.5%, and 98.8%, respectively. Ni/Ag exhibits the lowest reflectance due to strong absorption of light by the underlying Ni layer [14]. Further, the higher reflectance of ITO/CRS films in visible light than that of ITO/Ag films indicates that ITO/CRS films can efficiently substitute the normal ITO-Ag reflection systems.

Fig. 3(a,b) shows a top-view scanning electron microscope (SEM) image of the normal Ag-based FCLED and CRS-FCLED, respectively. Their layouts are nearly identical except for the reflective layer structure. The n-contact holes are evenly distributed over the entire area of the LED chip to enhance current spreading. The cross-sectional SEM images of both LEDs are shown in Fig. 3(c,d), and the corresponding schematic illustrations are shown in Fig. 3(e,f). As shown in Fig. 3(c,e), the diameter of the n-contact holes in the Ag layer is larger than that of the n-GaN contact holes in the normal Ag-based FCLEDs, to avoid Ag migration on forward current aging or bulk leakage by electrode destruction near the V-pit defect region [20]. However, this diameter mismatch can form an emission loss area. The light emitted from the sidewall of each n-GaN contact hole can be absorbed by n-pad metals with low reflectance, such as Cr and Au, which can decrease the light extraction efficiency. This emission loss phenomenon can be effectively reduced in CRS-FCLEDs. As shown in Fig. 3(d,f), at the edge of the Ag mirror, the DBR mirror continues to extend the reflection area, covering the upper and lower mesa gentle slope and the n-via area to maximize the reflection area. As a result, CRS-FCLEDs can achieve improved reflection performance compared with normal Ag-based FCLEDs.

Fig. 3. (a) Top-view SEM image of normal Ag-based FCLED. (b) Top-view SEM image of CRS-FCLED. (c) Cross-sectional SEM image of normal Ag-based FCLED milled by FIB along c-c direction. (d) Cross-sectional SEM image of CRS-FCLED milled by FIB along the d-d direction. (e) Schematic illustration of the light extraction of normal Ag-based FCLEDs. (f) Schematic illustration of the light extraction of CRS-FCLEDs.

The dependence of the forward voltage and LOP versus injection current for the normal Ag-based FCLED and CRS-FCLED are shown in Fig. 4(a). The I-V curves of the two LEDs are nearly identical, indicating that both have similar p-type and n-type contact spreading resistance^[21]. As the injection current increased, the output power of the CRS-FCLEDs showed better performance. At 350 mA, the LOP of the CRS-FCLED is 3.8% higher, which is further increased to 5.1% at 1000 mA. Finally, at 1500 mA, the LOP of the CRS-FCLED is 6.3% higher than that of the normal Ag-based FCLED. Meanwhile, the EQE of the CRS-FCLEDs improved by 3.4, 4.7, and 6.0% at 350, 1000, and 1500 mA, respectively [Fig. 4(b)]. The improvements can be attributed to the increased high reflection area, which helps to increase the light extraction efficiency. In addition, the degree of enhancement is larger at high injection currents, which can be explained by the better protection effect of the SiO₂/DBR/SiO₂ passivation layer that hindered Ag migration to the GaN material degradation with a large current density, which improves the EQE.

Fig. 4. (a) Forward voltage and LOP versus injection current for normal Ag-based FCLED and CRS-FCLED. (b) EQE versus injection current for normal Ag-based FCLED and CRS-FCLED.

Current crowding across the thick p reflective electrode adjacent to the n-electrode would result in surface leakage and output drop because of Ag migration on forward current aging ^[22]; therefore, Ag migration protection will determine the reliability and EQE of the flip-chip in high current injection conditions. In contrast with the normal Ag-based FCLED with a SiO₂ passivation layer that is less than 1 μm thick, the CRS structure covers the p reflective electrode and n-electrode with over 3- μm SiO₂/DBR/SiO₂ sandwich passivation layer, which further effectively blocks the path of Ag migration to the n-electrode.

Fig. 5. (a) Light emission distributions in the normal Ag-based FCLED. (b) Light emission intensity distributions in the CRS-FCLED.

The light emission intensity distributions of the normal Ag-based FCLEDs and CRS-FCLEDs, when driven by an injection current of 1500 mA [Fig. 5], shows that the total emission region of the CRS-FCLEDs is larger, owing to the increased reflective area at the sidewall and partial area of the n-GaN contact holes. Moreover, the emission intensity in the emission region around the n-GaN contact holes is explicitly higher than that in other emission regions. It has been reported that the number of photons generated in the active region around the electrode is significantly higher than that in other regions of the LED because of the current crowding effect around the electrode ^[23]. Therefore, even though the increased total reflective area of the CRS-FCLEDs is negligible, the light extraction efficiency can be significantly improved because the number of photons generated around the electrodes is considerably higher than that in other emission regions.

Fig. 6. (a) LED headlight module with dense matrix package. (b) Far-field radiation pattern of CRS-FCLED and normal Ag-based FCLED at 1500 mA.

Fig. 6(a) shows the LED module fabricated with our CRS-FCLEDs for use in a headlight. All the LED chips were packaged in an AlN ceramic matrix with high thermal conductivity. For headlight applications, the LED module must have a high packaging density to obtain the maximized optical density per unit area, with the distance between LED modules designed to be minimized within a short range of only 100-200 μm . However, high losses occur at large emission angles due to the narrow distance between chips, and this is not beneficial for the light output of the LED module. Fig. 6(b) shows the far-field angular light emission patterns of the normal Ag-based FCLEDs and CRS-FCLEDs. The operational current is 1500 mA for both LEDs, which is in accordance with the normal working conditions of the headlight module. Compared with the normal Ag-based FCLEDs, the intensity of the emission light from the CRS-FCLEDs is significantly increased, especially in the vertical direction, and the intensity of the emission light in the large angle direction is rarely increased. This result can be well explained by the additional reflection area of the CRS-FCLEDs. As the location of the additional reflective area is on the sidewall and covers part of the n-GaN contact holes, the photons emitted from the side wall can be extracted with the emission angle changing in the vertical

direction. As a result, the CRS-FCLED with the unique characteristic of strengthened light output in the vertical direction is suitable for use in a headlamp.

Fig. 7. Optical degradation of CRS-FCLED and normal Ag-based FCLED during high temperature operation life test.

Moreover, as shown in Fig. 7, the optical degradations of the CRS-FCLED and normal Ag-based FCLED at 85 °C were also investigated using an injection current of 1500 mA. After high temperature operation life test (1000 h), the light output power of CRS-FCLED decreased by 3.07%, whereas that of the normal Ag-based FCLED decreased by 9.92%. Clearly, the CRS-FCLED exhibits significantly smaller optical degradation and thus, offers a higher device reliability as compared to the normal Ag-based FCLED. Further, the forward current aging resulted in a noticeable output degradation in Ag-based FCLEDs due to the surface migration of Ag ^[24]. The CRS structure covered by the SiO₂/DBR/SiO₂ passivation layers consisting of three dielectric stack layers is found to be effective in suppressing the Ag migration. In addition, the mentioned structure is considerably effective in passivating the exposed surfaces of ITO and n-GaN layers after ICP etching, resulting in decreasing the trap density near the surface, minimizing the leakage current through the surface of the LED.

Discussion

In summary, FCLEDs with a novel composite reflection structure of Ag/SiO₂/DBR/SiO₂ were fabricated, which simultaneously improved the light extraction efficiency and light output in the vertical direction. Compared with the conventional FCLEDs with a single Ag mirror as the reflective layer, the reflective area of the CRS-FCLEDs is increased because the sidewall and part of the n-GaN contact holes had been covered by the highly reflective SiO₂/DBR/SiO₂ sandwich structure. As a result, the LOP of the CRS-FCLEDs increased by 6.3% at an operational current of 1500 mA, while the corresponding EQE was improved by 6.0%, and it exhibited markedly smaller optical degradation and thus higher device reliability as compared to the normal Ag-based FCLED. Moreover, the light emission intensity distributions and the far-field angular light emission pattern proved that it exhibited a higher light output in the vertical direction, suggesting that the CRS-FCLEDs have potential in headlamp lighting.

Method

Epitaxial growth. The LED samples were grown on the c-plane of the patterned sapphire substrate using the metal–organic chemical vapor deposition (MOCVD) method. Trimethylgallium (TMGa), trimethylindium (TMIn), trimethylaluminum (TMAI) and ammonia (NH₃) were used as gallium (Ga), indium (In), aluminum (Al) and nitrogen (N) sources material, respectively. Silane (SiH₄) and bis(cyclopentadienyl) magnesium (CP₂Mg) were used as the n-type doping and p-type doping sources, respectively.

Optical characterization. The surface morphologies of the LED structures were detected by using a top-view scanning electron microscope (ZEISS ΣIGMA). The reflectance as a function of wavelength was measured using a Spectrophotometer (HITACHI U-3900). Forward voltage and LOP versus injection current were measured by integrating sphere (EVERFINE HAAS-3000). The light emission distributions of both LED structures were obtained by thermal Imaging Spectrometer (OPHIR Photonics spiricon). Far-field radiation pattern of the LED samples were measured through spatial spectral distribution test system (EVERFINE GO-SPEX100). The optical degradations of LED samples were measured by using (EVERFINE LT-300A) accelerated aging and life test system.

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Author Contributions

L.X. conceived the experiments, L.X. carried out optical analysis, SEM of the LED samples, and J.L.Z. performed the Far-field radiation and Light emission distributions measurement and analysis, H.Q.S contributed the calculation result of reliability. Z.Z.C. and Z.Y.G. reviewed the manuscript.

Additional Information

Competing Interests: The authors declare that they have no competing interests.

Figures

Figure 1

Main fabrication process of the CRS-FCLED.

Figure 2

Reflectances of Ni/Ag, ITO/Ag, and ITO/CRS films

Figure 3

(a) Top-view SEM image of normal Ag-based FCLED. (b) Top-view SEM image of CRS-FCLED. (c) Cross-sectional SEM image of normal Ag-based FCLED milled by FIB along c-c direction. (d) Cross-sectional SEM image of CRS-FCLED milled by FIB along the d-d direction. (e) Schematic illustration of the light extraction of normal Ag-based FCLEDs. (f) Schematic illustration of the light extraction of CRS-FCLEDs.

Figure 4

(a) Forward voltage and LOP versus injection current for normal Ag-based FCLED and CRS-FCLED. (b) EQE versus injection current for normal Ag-based FCLED and CRS-FCLED.

Figure 5

(a) Light emission distributions in the normal Ag-based FCLED. (b) Light emission intensity distributions in the CRS-FCLED.

Figure 6

(a) LED headlight module with dense matrix package. (b) Far-field radiation pattern of CRS-FCLED and normal Ag-based FCLED at 1500 mA

Figure 7

Optical degradation of CRS-FCLED and normal Ag-based FCLED during high temperature operation life test.