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Aspect ratio engineering of microlens arrays in thin-film flip-chip light-emitting diodes

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Light extraction efficiency of thin-film flip-chip InGaN-based light-emitting diodes (LEDs) with a TiO_2 microlens arrays was calculated by employing the finite-difference time-domain method. The microlens arrays, formed by embedding hexagonal close-packed TiO_2 sphere arrays in a polystyrene (PS) layer, were placed on top of the InGaN LED to serve as an intermediate medium for light extraction. By tuning the thickness of the PS layer, in-coupling and out-coupling efficiencies were optimized to achieve maximum light extraction efficiency. A thicker PS layer resulted in higher in-coupling efficiency, while a thinner PS layer led to higher out-coupling efficiency. Thus, the maximum light extraction efficiency becomes a trade-off between in-coupling and out-coupling efficiency. In addition, the cavity formed by the PS layer also affects light extraction from the LED. Our study reveals that a maximum light extraction efficiency of 86% was achievable by tuning PS thickness to 75 nm with maximized in-coupling and out-coupling efficiency accompanied by the optimized resonant cavity condition.

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1. INTRODUCTION

III-nitride-based light-emitting diodes (LEDs) have significantly progressed for practical implementation in solid-state lighting applications [1–4]. The technology also has been incorporated into various market segments, such as automotive lighting, indoor and outdoor lighting, medical applications, and lifestyle products [1–4]. The advances in thin-film flip-chip (TFFC) InGaN blue light-emitting diodes (LEDs) and phosphor materials provide key insights into the commercialization of the white LED technology. In the past decades, significant effort has been devoted to address various fundamental limiting issues in InGaN blue LEDs, specifically by improving internal quantum efficiency [5–9], addressing the efficiency-droop issue [10–15], and optimizing light extraction efficiency [16]. Addressing the internal and extraction efficiencies in III-nitride LEDs is important, as both parameters define the net power conversion efficiency in the devices. The improvement in light extraction efficiency in III-nitride LEDs needs to be achieved with a cost-effective method for ensuring industrial implementation.

Numerous approaches were employed to improve light extraction efficiency [17–22]. The use of surface roughness on TFFC LED resulted in light extraction efficiency of 65%, which is much higher than that of conventional top-emitting LED (4%) and planar TFFC LED (27%) [23–25]. However, the nonuniform light emission and the damage on the contact caused by chemical etching represent an important concern for the LED with surface roughness. To solve the nonuniform issues of LED with surface roughness, photonics crystal structure formed by e-beam lithography was employed to enhance light extraction efficiency of TFFC LED, resulting in light extraction efficiency of 72% [26].

Recently, the use of self-assembled SiO_2 microsphere and microlens arrays had been investigated for LEDs and OLEDs implementation [27–36]. The use of this self-assembly method enables a low-cost and wafer-scale implementation. The optimum light extraction efficiency was achieved by using an index-matched anatase TiO_2 sphere array [33]; recent results have shown an optimum extraction efficiency of 75% as obtainable for TFFC LEDs with TiO_2 microsphere arrays [36].

In this paper, light extraction efficiency of TFFC LED with TiO_2 microlens arrays was numerically investigated. Further enhancement is anticipated by embedding microsphere arrays in a planar polystyrene (PS) layer to form TiO_2 microlens arrays. Although experimental work had shown qualitative improvement from the use of microlens arrays on the LEDs, no quantitative improvement has been fully investigated for identifying the optimum extraction efficiency achievable in TFFC LEDs from the use of the microlens arrays. This comprehensive study includes the optimizations of the resonant cavity effect, packing density, packing configuration, refractive index of the sphere, and aspect ratio of the lens arrays.

Light extraction efficiency of TFFC LED with a PS layer and microlens arrays was calculated by employing the finite-difference time-domain (FDTD) method. Schematics of the TFFC LED structures with a PS layer (for comparison purpose) and microlens arrays studied in this work are shown in Figs. 1(a) and 1(b), respectively. The planar TFFC LED structure is formed by an InGaN/GaN active region sandwiched by p-GaN and n-GaN [36], and the refractive index of GaN was set to 2.5 in our simulation. The bottom layer of the TFFC LED was set to be a metallic layer, which was assumed to be a perfect mirror with 100% reflectance. By taking into account the computational efficiency, the simulation domain was set to $10\ \mu m \times 10\ \mu m$ with perfectly matched layer (PML) boundary conditions applied to the lateral boundaries and perfect electric conductor (PEC) boundary conditions applied to the bottom of the LED. The grid size of the simulation was set to 10 nm to ensure computational accuracy. Besides, the simulation time was also set to be long enough to ensure the stability of the field output. One dipole was chosen to be the photon source within the quantum well active region and positioned in the center of the active region. The emission wavelength used in this simulation was set to $\lambda \sim 505$ nm. Light extraction efficiency was calculated as the ratio of the optical output power extracted out from the top of LED to the total power generated by the dipole. Details of the FDTD simulation method were reported in our recent work [33,35,36].

Our previous work showed that the 400 nm diameter anatase TiO_2 sphere with close-packed hexagonal pattern arrays exhibited the highest light extraction efficiency for a GaN-based LED [33,35]. Note that our prior work showed that the LED with microlens arrays is expected to have higher light extraction efficiency than that of the LED with microsphere arrays [28]. As shown in Figs. 2(a)–2(c), higher far-field intensity is observed for the TFFC LED with TiO_2 microlens arrays as compared with that of planar TFFC LED and TFFC LED with TiO_2 microsphere arrays. This indicates the potential of TFFC LED with TiO_2 microlens arrays in exceeding the reported highest light-extraction efficiency obtained by TFFC LED with TiO_2 microsphere arrays.

The TFFC LED structure with microlens arrays studied in this simulation was optimized taking into account the cavity effect. The microlens arrays are formed by embedding the 400 nm diameter anatase TiO_2 sphere arrays into a planar PS layer, and the refractive index of PS was set to 1.6 [37]. As the variation of the PS layer thickness covering the microsphere results in the aspect ratio engineering of the microlens arrays deposited on the TFFC LEDs, light extraction efficiency of LED with microlens arrays with different aspect ratios was calculated by tuning the PS thickness (h_{PS}) from 0 to 400 nm. Note that the microlens arrays with various aspect ratios can be experimentally obtained by thermal annealing TiO_2/PS binary sphere arrays under different conditions [30]. In this study, a planar LED structure with p-GaN thickness of 160 nm and

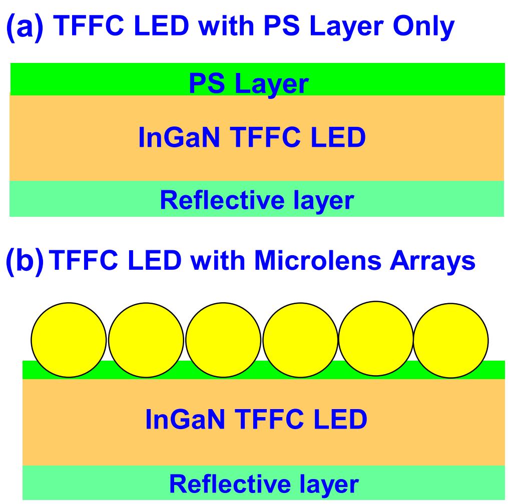

Fig. 1. Schematics of TFFC LED with (a) planar PS layer and with (b) microlens arrays.

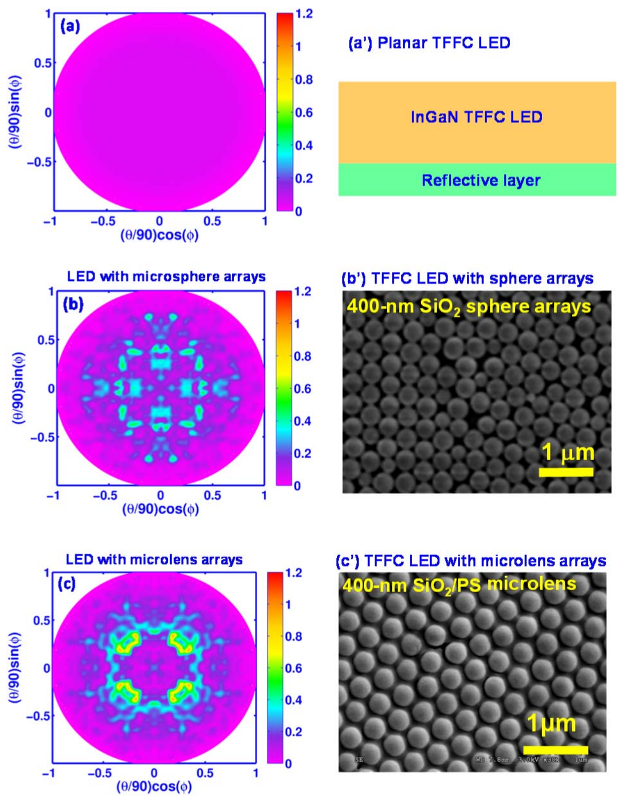

Fig. 2. (a) Contour plot of far-field intensity and corresponding schematic for planar TFFC LED, contour plot of far-field intensity for TFFC LED with (b) 400 nm TiO_2 microsphere arrays and with (c) TiO_2 PS microlens arrays. For illustrating the structures (as examples), the corresponding (a'), (b'), and (c') refer to the planar LED, TFFC LED with microsphere array, and TFFC LED with microlens array, respectively.

n-GaN thickness of 500 nm was used as a reference structure, as schematically illustrated in Fig. 2(a').

2. RESULTS AND DISCUSSION

The ability to tune the thickness of a PS layer results in the capability of engineering microlens arrays with various aspect ratios, as shown in Figs. 3(a')–3(d'). By embedding TiO_2 microsphere arrays in the PS layer with various thicknesses on top of the TFFC LED, the far-field intensity of the LED can be significantly modified due to the changes of the aspect ratios, as seen in Figs. 3(a)–3(d). Note that the PS layer with a thickness above 200 nm provides lens arrays with a hemispherical aspect ratio. More importantly, our results, as shown in Fig. 3, indicate that the highest far-field intensity is observed for the TFFC LED with microlens arrays with a PS layer thickness of 75 nm, thus implying the importance of optimizing the aspect ratio of the microlens arrays for optimum light extraction enhancement with this structure.

Our analysis indicates that in-coupling of wave-guide modes into the sphere arrays (in-coupling efficiency) and subsequent extraction of those coupled light (out-coupling efficiency) are the two key factors in optimizing light extraction enhancement for the TFFC LED with microlens arrays. In the case of LED with microsphere arrays [36], the limited contact between the spheres and the LED surface results in low in-coupling efficiency, thus preventing further enhancement of the light extraction efficiency. For the LED with microlens arrays, the spheres are partially embedded into the PS layer, and the light can be transmitted through the PS layer to spheres. Thus, the in-coupling efficiency increases with the increase in PS thickness. However, the out-coupling efficiency decreases as the PS thickness increases due to the trapping of light within the sphere arrays. When the optimum PS thickness is applied, the amount of photons to be coupled into and extracted out of the spheres is optimized. Therefore, the far-field intensity of the TFFC LED with microlens arrays [see Figs. 3(a)–3(d)] increases initially before the PS thickness reaches 75 nm and then starts to decrease.

In comparison, a similar trend is also observed for the TFFC LED with only a planar PS layer. The far-field intensity was calculated for TFFC LED with a planar PS layer, as the PS layer thickness is varied from 0 nm (no PS layer) up to 350 nm, as shown in Fig. 4. The far-field radiation patterns for the LEDs with a planar PS layer shows only angular dependency and symmetrically azimuthal distribution. The inner and outer radiation rings are attributed to the direct emission from the InGaN QWs and the reflected emission from PEC reflector, respectively. Note that the angular dependency of the light distribution also varies as the PS thickness changes. This is attributed to the interference between the light traveling forward and the light traveling backward, which was reflected back by the metallic layer. Therefore, the constructive interference took place at different angles for the LED with different PS thicknesses.

By comparing the TFFC LEDs with microlens arrays and with the planar PS layer, as shown in Figs. 3 and 4, respectively, a much higher far-field intensity was observed for the LED with microlens arrays than that of the LED with PS layer. Note also that, for the LED with microlens arrays, the far-field radiation patterns exhibit angular and azimuthal dependency, as shown in Fig. 3.

By setting proper boundary conditions, our simulation integrated the light radiation intensity over all solid angles in calculating the light extraction efficiency. The effect of a microlens array on light extraction efficiency of the TFFC LEDs is then further investigated. The calculated light extraction efficiencies of TFFC LEDs with microlens arrays are shown in Fig. 5. The extraction efficiency of the TFFC LED with microsphere arrays ($h_{PS} = 0$ nm) is ~40%. In the case of larger PS thickness

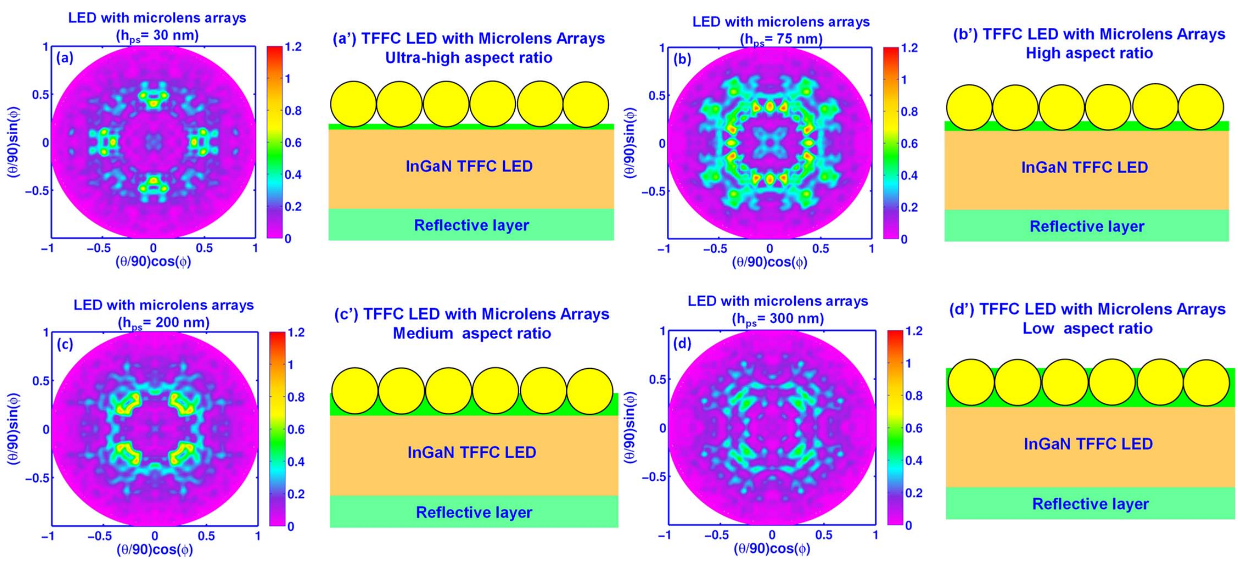

Fig. 3. Contour plot of far-field intensity and the corresponding schematic structures of TFFC microlens arrays LED with PS thickness of (a) 30 nm, (b) 75 nm, (c) 200 nm, and (d) 300 nm. Schematics (a'), (b'), (c'), and (d') refer to the corresponding TFFC LEDs with various aspect ratios.

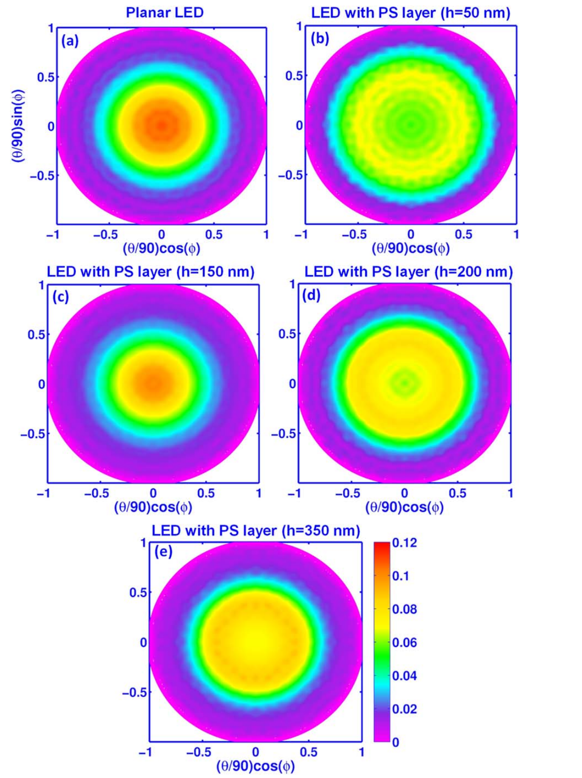

Fig. 4. Contour plot of far-field intensity of (a) planar LED and LED with different thickness of planar PS layers: (b) 50 nm, (c) 150 nm, (d) 200 nm, and (e) 350 nm.

($h_{PS} \sim 150$–400 nm) embedding the TiO_2 microsphere arrays, the light extraction efficiencies are obtained as ~50% up to ~60%.

By designing the microlens arrays with a high aspect ratio ($h_{PS} \sim 50$-nm up to 150 nm), light extraction efficiency in TFFC LEDs is significantly enhanced to the range of 70% up to 86%. Specifically, maximum light extraction efficiency of 86% for TFFC LEDs is achieved by using the microlens arrays with a 75 nm PS layer, resulting in 6.8 times enhancement compared with that of the reference planar TFFC LED with 12.6% light extraction efficiency. Further increase of the PS thickness ($h_{PS} > 75$ nm) for the TFFC LED leads to the reduction of light extraction efficiency.

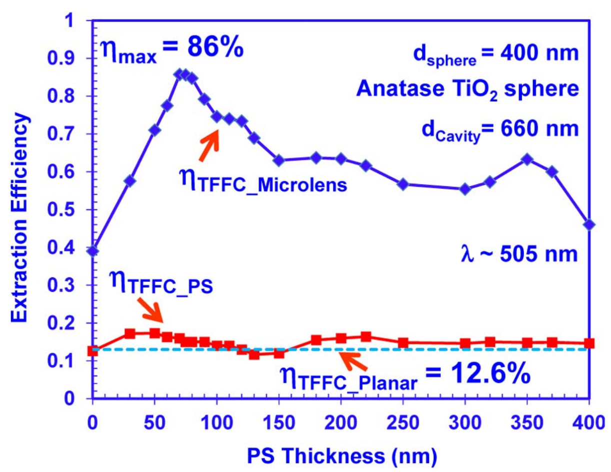

Fig. 5. Light extraction efficiency of TFFC LED with microlens arrays compared with LED with planar PS layer and the planar TFFC as references.

In addition, light extraction efficiency of TFFC LEDs with only a planar PS layer also varies with PS thickness, as shown in Fig. 5. While the overall extraction efficiency is much lower than that of an LED with microlens arrays, a similar trend can be observed in Fig. 5 for the TFFC LED with a planar PS layer. In this case, the PS layer deposited on top of the LED served as an antireflection coating to reduce the Fresnel reflection. Additionally, the resonant cavity effect also plays a trivial role on light extraction efficiency. As the thickness of PS layer changed, the constructive interference can be achieved, which leads to the enhancement in light extraction efficiency.

3. CONCLUSION

In conclusion, light extraction efficiency of TFFC LEDs with TiO_2 microlens arrays was calculated by the FDTD method. The microlens arrays were formed by embedding a 400 nm diameter anatase TiO_2 sphere into a planar PS layer. The periodic microlens structures served as an intermediate medium to enlarge the light escape cone by coupling the wave-guiding mode into a sphere and then extracting the coupled light out of the sphere. By tuning the PS thickness, the in-coupling and out-coupling efficiency were optimized; thus, optimum light extraction efficiency of 86% can be achieved with a 75 nm PS layer, which is much higher than that of the planar LED (12.6%) and that of the LED with only the sphere arrays (39%).

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