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Structural Optimization of Novel MicroLED for Enhanced Performance

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Abstract

MicroLED is regarded as a core technology for next-generation displays, but its low light extraction efficiency (LEE) remains a critical bottleneck hindering industrialization. The primary cause of this issue lies in the severe total internal reflection at interfaces between high-index semiconductor layers and surrounding low-index media, which traps a large portion of generated photons within the chip. In this paper, based on the finite-difference time-domain (FDTD) method, which is well-suited for resolving wavelength-scale optical interactions in complex geometries, we systematically investigate the effects of electrode layout, surface microstructure, and mesa geometry on the LEE of flip-chip MicroLED chips. A hybrid mesh electrode achieves an LEE of 39.5% while maintaining good current uniformity. Randomly roughened surfaces and photonic crystal structures improve the LEE to 48.5% and 52.3%, respectively. Furthermore, we compare regular- and inverted-trapezoidal mesa structures. The inverted-trapezoidal structure with a sidewall angle of 10° achieves a peak LEE of 0.38, which is 35% higher than that of the vertical sidewall reference, while the regular-trapezoidal structure with a sidewall angle of 5° reaches 0.30 (5% improvement). The enhanced performance of the inverted-trapezoidal configuration is attributed to the fact that inclined sidewalls help to redirect laterally trapped photons towards the top escape surface by altering the angle of incidence upon internal reflection. Through multi-parameter collaborative optimization based on the inverted-trapezoidal shape, a peak LEE of 64.2% is finally achieved. This work provides a systematic theoretical basis and practical structural optimization strategies for high-performance MicroLED chips.

Keywords

MicroLED; FDTD; Simulation; Structural Optimization.

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1. Introduction

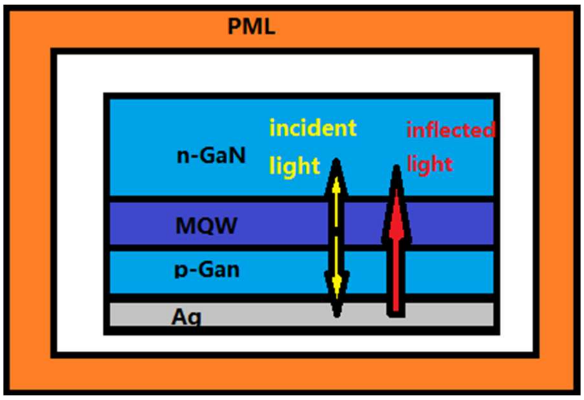


Fig. 1 MicroLED chip structure.

MicroLED has become a research hotspot in high-end displays due to its advantages of high brightness, low power consumption, and long lifetime. These characteristics make it a promising candidate for applications ranging from augmented reality and virtual reality headsets to large-area televisions and automotive displays. However, severe total internal reflection at the interface between high-refractive-index materials (e.g., GaN) and air traps a large number of photons inside the chip, resulting in an LEE typically below 30% [1]. To overcome this bottleneck, various approaches such as flip-chip structures, surface roughening, photonic crystals, and mesa shaping have been proposed [2]. Nevertheless, most studies focus on single-parameter optimization, lacking systematic collaborative design. In practical device development, the interactions between different structural features can lead to non-trivial combined effects that are not captured by isolated parameter studies. For instance, while an inverted-trapezoidal mesa shape can redirect laterally propagating light upward, its effectiveness may be further amplified or modified by the presence of a photonic crystal on the top surface. Therefore, this paper employs the FDTD method to build a three-dimensional simulation model of a flip-chip MicroLED, systematically investigates the influence of electrode, surface microstructure, and mesa geometry on LEE, and proposes a multi-parameter collaborative optimization scheme.

2. Simulation Method and Model Setup

A 3D FDTD model of a flip-chip blue GaN-based MicroLED is constructed using ANSYS Lumerical software. The chip size is 20 μm × 20 μm, which is representative of typical pixel dimensions used in high-resolution microdisplays. The main structural layers include: N-GaN (3.0 μm), multiple quantum well (MQW) active region (100 nm), P-GaN (200 nm), ITO transparent conductive layer (150 nm), Ag reflector, and a planar encapsulation layer ($n = 1.53$). Multiple randomly oriented dipole sources are used to simulate spontaneous emission with a central wavelength of 450 nm. These dipoles are distributed throughout the MQW region to mimic the isotropic nature of carrier recombination. The refractive indices at 450 nm are set as: $nGaN = 2.42$, $nITO = 1.95$, and the complex refractive index of Ag is $0.15 + 3.0i$, which corresponds to a reflectivity above 95% at the emission wavelength. The computational domain is surrounded by perfectly matched layer boundary conditions to absorb outgoing radiation and avoid artificial reflections that would otherwise contaminate the near-field distribution. A grid convergence test (maximum grid size ≤ 15.5 nm) and comparison with published results validate the accuracy of the model [3].

3. Results and Discussion

3.1 Electrode Layout Optimization

Four electrode patterns (solid disk, ring, mesh, cross) are compared. The solid disk electrode exhibits the highest LEE (41.2%) due to its large reflective area, but its current uniformity is poor (only 65% of the center value at the chip edge). Such non-uniformity arises from current crowding near the contact periphery, which can lead to localized heating and efficiency droop under high injection conditions. A hybrid mesh electrode (20% coverage) achieves an LEE of 39.5% while improving current uniformity to over 80%. This design represents an effective compromise between optical reflectivity and electrical performance, ensuring that the majority of the active area emits light homogeneously. Moreover, the Ag electrode yields an absolute LEE increase of about 1.8 percentage points compared to Al due to its higher reflectivity in the blue spectral region. This result is consistent with previous studies on reflective electrodes for flip-chip LEDs [2].

3.2 Light-Extraction Surface Microstructures

A randomly roughened surface (root-mean-square roughness 150 nm, correlation length 300 nm) increases the LEE from 31% (smooth surface) to 48.5%. The introduction of surface roughness helps to scatter photons into the escape cone, thereby mitigating the total internal reflection limitation. The correlation length and roughness amplitude were chosen to provide broadband scattering across the blue emission spectrum. A two-dimensional photonic crystal structure (lattice constant 280 nm, holeradius-to-period ratio 0.35, depth 200 nm) utilizes the photonic bandgap effect to further raise the LEE to 52.3% and also provides a certain beam collimation capability. The lattice constant is selected to satisfy the Bragg condition for guided modes near 450 nm, facilitating efficient diffraction into leaky modes. These findings agree with reports that periodic nanostructures can effectively extract guided modes in GaN-based LEDs [4].

3.3 Regular- and Inverted-Trapezoidal Mesa Structures

To investigate the effect of sidewall inclination on light extraction, we compare three mesa profiles: vertical sidewalls (reference), regular-trapezoidal (narrower top than bottom), and inverted-trapezoidal (wider top than bottom). The sidewall angle θ is defined as the deviation from the vertical direction. The chip footprint remains 20 μm × 20 μm at the bottom for all cases. It is important to note that the choice of mesa geometry is particularly critical for small pixel sizes, where sidewall interactions can dominate the overall optical loss and extraction behavior.

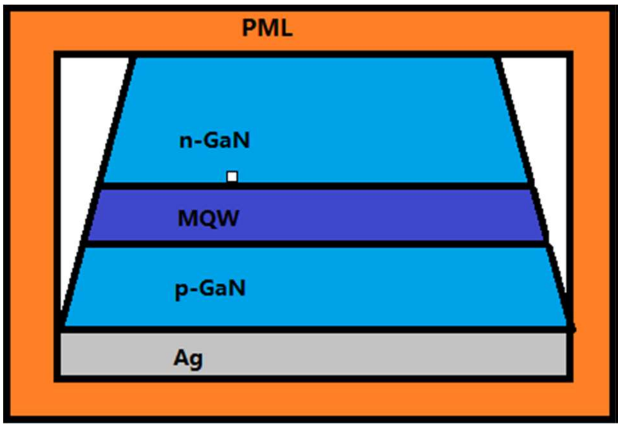


Fig.2 Trapezoidal shape

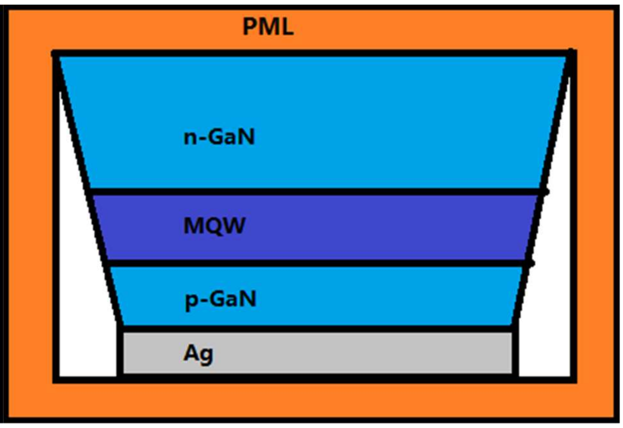
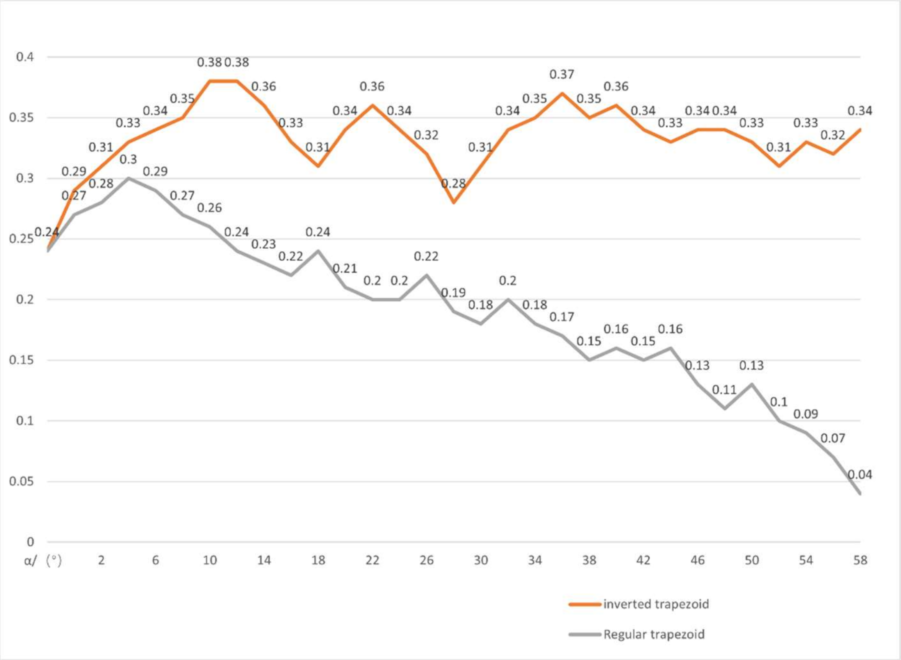


Fig.3 Inverted trapezoidal shape

Table 1. Light extraction efficiency for two different shapes



Simulation results are shown in Table 1. As the sidewall angle increases from 0° to 15°, the LEE of the inverted-trapezoidal structure first rises and then slightly decreases, peaking at θ = 10° with a value of 0.38. This represents a 35% improvement compared to the vertical sidewall structure

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(LEE ≈ 0.281). The improvement is attributed to the fact that inclined sidewalls redirect laterally propagating photons upward, increasing the chance of escaping through the top surface. Specifically, when a photon guided in the high-index GaN layer strikes an outwardly slanted sidewall, the angle of incidence relative to the sidewall normal is reduced, which can shift the reflected ray towards a more upward trajectory. In contrast, the regular-trapezoidal structure (narrower top) yields a moderate improvement, peaking at $\theta = 5°$ with an LEE of 0.30, which is only 5% higher than the vertical reference. For larger regular-trapezoidal angles, LEE declines due to increased sidewall trapping and multiple internal reflections that promote absorption. The inverted-trapezoidal shape is therefore more effective in breaking guided modes and enhancing light extraction. These findings are consistent with previous reports on tapered mesa structures [5].

4. Conclusion

In this paper, based on the FDTD method, we systematically investigated the effects of electrode layout, surface microstructure, and mesa geometry on the LEE of flip-chip MicroLEDs. A multi-parameter collaborative optimization strategy combining a hybrid mesh electrode, a photonic crystal surface, and an inverted-trapezoidal mesa structure (sidewall angle 10°) is proposed. The hybrid mesh electrode, with a 20% metal coverage, was shown to deliver an LEE of 39.5% while simultaneously improving current spreading uniformity to over 80%, thereby addressing a key trade-off between optical reflectivity and electrical performance.

The introduction of surface microstructures proved highly effective, with a photonic crystal surface achieving an LEE of 52.3% and also imparting a degree of beam collimation that is beneficial for directional display applications. Among the mesa geometries examined, the inverted-trapezoidal shape alone improves LEE by 35% compared to the vertical sidewall case, substantially outperforming the regular-trapezoidal shape (5% improvement at 5°). This pronounced difference underscores the importance of sidewall orientation in compact MicroLED pixels, where even small geometric adjustments can have a significant impact on photon escape probability.

When these three optimized features are integrated into a single device architecture, the final optimized structure achieves a peak LEE of 64.2%, more than double the typical value reported for unoptimized planar MicroLEDs. This substantial enhancement provides a strong theoretical basis and a practical solution for the design of high-performance MicroLED chips. The systematic multi-parameter approach presented here can serve as a valuable design guideline for device engineers seeking to maximize light extraction in next-generation MicroLED emitters. Looking forward, future work will incorporate electro-thermal-optical multi-physics simulations to capture the coupled interactions between current injection, Joule heating, and optical extraction efficiency under realistic operating conditions. Furthermore, experimental fabrication and characterization of the proposed optimized structures will be pursued to validate the simulation predictions and to further advance the ongoing industrialization and commercial adoption of MicroLED technology for applications spanning augmented reality, virtual reality, and ultra-high-definition large-area displays.

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