Fly-Eye Structures for Increasing MicroLED Light Extraction

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Fly-Eye Structures for Increasing MicroLED Light Extraction

ABSTRACT

This disclosure describes fly-eye nanostructures for increasing light extractions from semiconductor layers of micro light emitting diodes (microLEDs). Disposing a fly-eye nanostructure layer on a semiconductor layer having a high refractive index increases the percentage of light that escapes an air-to-semiconductor interface when the semiconductor layer has a high refractive index. As a result, the efficacy of light emitting semiconductors is improved. From a plan view, the fly-eye nanostructures include raised structures that may appear similar to brain structures, a hedge maze, or a fingerprint. The raised structures may appear closely-packed, random, and sinuous.

KEYWORDS

- Fly-Eye nanostructure
- Light extraction
- Optical layer
- Semiconductor to Air Interface
- microLED
- Total internal reflection (TIR)
- Fresnel reflection
- Light Reflection Reduction

BACKGROUND

The semiconductor layers of light emitting devices (e.g. LEDs or microLEDs) tend to have a high index of refraction. For example, gallium nitride (GaN) has a refractive index of approximately 2.3-2.4 in the visible light range (approximately 380 nm to 700 nm). An interface
between a high refractive index semiconductor layer and air (refractive index of ~1) increases the likelihood of light emissions from the semiconductor layer being confined to the semiconductor layer due to total internal reflection (TIR) and/or Fresnel reflections, as shown in FIG. 1.

![FIG. 1](image)

In some contexts, only a small portion of the emitted light escapes the semiconductor layer while the remaining portion of the light is confined to the semiconductor layer because of total internal reflection (TIR) and/or Fresnel reflections. In addition to reducing the efficacy of light emitting structures, the undesirable reflection(s) result in pixel cross-talk where closely grouped LEDs form a display pixel array since the light emitted in one pixel may exit an adjacent pixel. In other words, the semiconductor layer functions as an unintended lightguide that transfers the emission light to another pixel. This reduces the contrast of pixels in an LED or microLED pixel array.

Traditional approaches to increase the efficiency of emission light exiting the semiconductor layer include disposing a multilayer dielectric anti-reflection (AR) on the semiconductor layer. In one traditional approach, the top of the semiconductor layer is roughened or textured or lithographically patterned to enhance the light extraction of emitted
light. Alternatively, lower-index transparent encapsulants (e.g., silicones, epoxy, glass w/ n ~ 1.3 to ~1.7 for visible light) with shaped lenses (e.g., hemispherical) can increase total extracted light. Another conventional approach includes disposing a moth-eye layer including nanopillar or nanocone structures on the semiconductor layer to increase the light extraction efficiency of LEDs. However, these structures are more effective at extracting light at incidence angles that are normal to a boundary of the semiconductor layer and therefore more effective at reducing Fresnel reflection losses while TIR losses still largely remain.

DESCRIPTION

This disclosure includes a fly-eye structure layer disposed on a semiconductor layer to assist in extracting emission light generated in the semiconductor layer, as shown in FIG. 2.

FIG. 2 illustrates a side view of a light emitting semiconductor structure found in LEDs and microLEDs. The semiconductor layer may be GaN or gallium-indium-nitride (GaInN) or other semiconductor material, depending on the wavelength of the emission light of the LED. The semiconductor layer includes an N-doped sublayer and a P-doped sublayer to stimulate
emissions of light from the semiconductor layer. While FIG. 2 shows the P-doped sublayer disposed between the fly-eye structure and the N-doped sublayer, the N-doped sublayer may be disposed between the fly-eye structure and the P-doped sublayer in some implementations.

As seen in FIG. 2, in presence of the fly-eye-structure, emitted light from the semiconductor layer becomes extracted light. In the absence of the fly-eye-structure, emitted light encountering the boundary of the semiconductor layer at a similar incidence angle is confined by TIR, as seen in FIG. 1. Thus, the fly-eye structure assists in increasing the extraction of emission light from the semiconductor layer.

Published research that shows images of fly-eye structures that occur in nature is available. For example, FIGs. 1-D, 1-D”’, 1-E, and 1-E’’ of [1] illustrate example top views of actual fly-eye structures of *Drosophila melanogaster*. FIG. 1-D”’ is a zoomed-in view of the fly-eye illustrated in FIG. 1-D. FIG. 1-D”’ may be approximately 2 microns across. FIG. 1-E”’ is a zoomed-in view of the fly-eye illustrated in FIG. 1-E. FIG. 1-E”’ may be approximately 2 microns across. The fly-eye structures of FIGs. 1-D’’ and 1-E”’ CAN be considered nanostructures. Viewed from above, the fly-eye structures of FIGs. 1-D”’ and 1-E”’ combine to appear similar to a brain, a hedge maze, or fingerprint, with the raised structures seeming close-packed, random, and sinuous. FIG. 1D of [2] illustrates an additional example top view of actual fly-eye structures of *Delia platura*, a different species of fly.

A mathematical description of the fly-eye structure can include some or all of the following features:

- **Width**: Half or less of the wavelength of the relevant color of light. If the fly-eye structure is designed to increase extraction across multiple wavelengths, the width may be half or less (in...
nm) of the shortest wavelength of interest. For example, to extract red light between 620 nm and 640 nm, the width of the fly-eye structures may be 310 nm wide or less.

- **Length**: Typically, 0.5-2X the shortest relevant wavelength, with no regularly repeating patterns. Structures longer than 5X the wavelength are possible, but the structure must bend by at least 10 degrees every 5 wavelengths.

- **Height**: Approximately equal to the width of the structure, but can be greater than half the shortest wavelength of interest.

- **Cross-section**: Wider at the base, narrower at the top. Rounded (for example, hemispherically or parabolically) at the top. The gaps between structures may also be rounded, or may be abrupt. The sidewall shape may be approximately triangular, gaussian, or \( \sin^2(x) \).

- **Spacing**: Gaps between structures at the base may be 20% or less of the shortest relevant wavelength. Gaps between structures at half the height of the structures are designed to be equal to or less than the width of the structure at that height.

FIG. 3 illustrates an example of a display pixel array having integer \( n \) microLED display pixels arranged in integer \( x \) columns (\( C_1 \ldots C_x \)) and \( y \) rows (\( R_1 \ldots R_y \)).
In the microLED display context, a fly-eye structure can be disposed over the microLED display pixels to increase extraction efficiency of the light emitted from the microLED display pixels and to decrease optical crosstalk resulting from Fresnel reflection or TIR light being emitted by adjacent microLED display pixels.

The foregoing description of the configurations of microLED displays with fly-eye structures are illustrative. Various modifications to the configurations and variations can be made, e.g., based on the specific application, the semiconductor technology used, etc.

CONCLUSION

This disclosure describes fly-eye nanostructures for increasing light extractions from semiconductor layers of micro light emitting diodes (microLEDs). Disposing a fly-eye nanostructure layer on a semiconductor layer having a high refractive index increases the percentage of light that escapes an air-to-semiconductor interface when the semiconductor layer
has a high refractive index. As a result, the efficacy of light emitting semiconductors is improved. From a plan view, the fly-eye nanostructures include raised structures that may appear similar to brain structures, a hedge maze, or a fingerprint. The raised structures may appear closely-packed, random, and sinuous.

REFERENCES
