Light Extraction Efficiency in GaN-Based Light-Emitting Diode Technology

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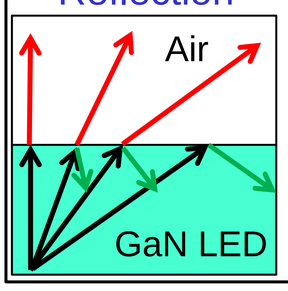
Introduction

GaN-based light-emitting diodes (LEDs) have drawn much attention in recent years for solid state lighting and display applications, and thus the problem of poor light extraction efficiency has arisen. Several methods have been examined to increase this extraction efficiency, and are discussed in this work. While these methods increase the extraction efficiency, they are expensive and non-uniform. In this work, rapid convective deposition (RCD) is used to modify the surface properties of GaN-based LEDs to improve the extraction efficiency by two to three times.[2] The use of microlens array LEDs is extended from 1-µm SiO_2 microspheres to 500-nm and 400-nm SiO_2 nanospheres to optimize the extraction efficiency of GaN-based LEDs. By varying the deposition speed and blade angle, it is possible to achieve optimized close-packed 2-D monolayer micro/nanolens structures.

Problems with LED Emission

Total Internal Reflection

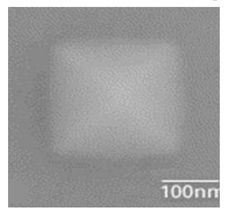


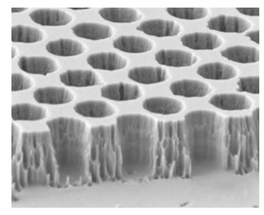
1. Narrow photon escape cone
2. Fresnel Effect

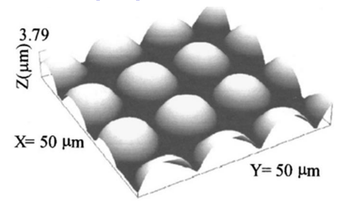
→ These result in low extraction efficiency (fraction of generated photons in air)

Alternate Solutions

Related works have discussed methods to increase extraction efficiency. Of these, surface roughening and roughened mesa sidewalls require photochemical etching, and thus result in nonuniform structures. Photonic crystals, sapphire microlenses, and self-assembled lithography p-GaN patterning use lithographic procedures, which are high in cost and therefore impractical for realistic production.[2] Nanopyramids, while effective, must be grown. This takes both time and expensive equipment.



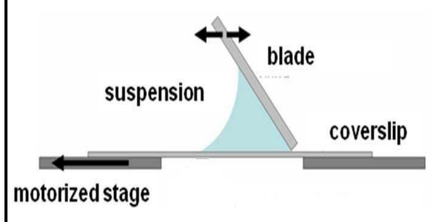


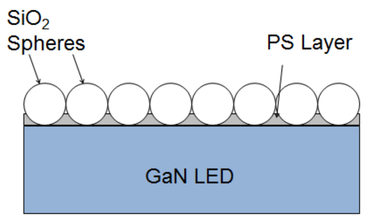


Left: Nanopyramid[4]
Center: Photonic Crystal[5]
Right: Sapphire Microlens[6]

Solution: SiO_2/PS Microlens Array on LED

By depositing a monolayer array of SiO_2 microspheres onto the GaN LED, the scattering angle is increased. Smaller polystyrene (PS) spheres are deposited with the SiO_2 to be annealed at 140°C, forming a tunable layer between the SiO_2 spheres. A monolayer structure is obtained by injecting 7µL of SiO_2/PS suspension onto the edge between the blade and glass substrate, and dragging the blade along the substrate with a linear motor.[3]

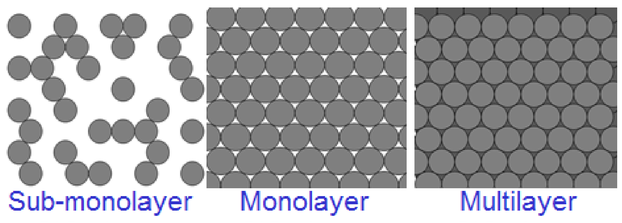




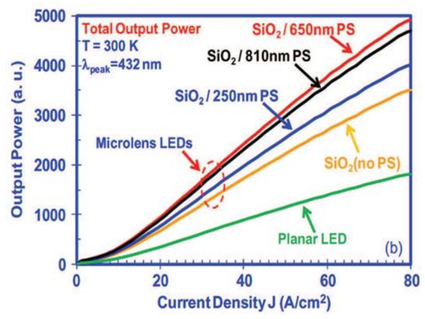
Left: Diagram of RCD Setup[1]
Right: Microlens Array on LED

Microlens Arrays of Various SiO_2 Spheres

This work applies the RCD method to SiO_2 nanospheres at 500-nm and 400-nm. At each sphere size, deposition speed and blade angle must be optimized to attain a 2-D hexagonal close-packed monolayer array. If these conditions are not optimized, then a sub-monolayer or multilayer deposition will occur and extraction efficiency will not be improved.



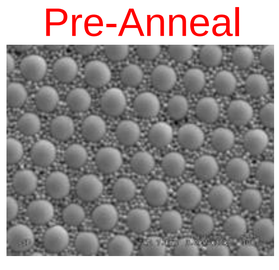
Sub-monolayer SiO_2 Array | Monolayer SiO_2 Array | Multilayer SiO_2 Array

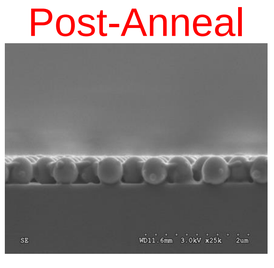


Total Output Power for 1-µm SiO_2[2]

500-nm SiO_2/75-nm PS

Top View Pre-Anneal | Side View Post-Anneal

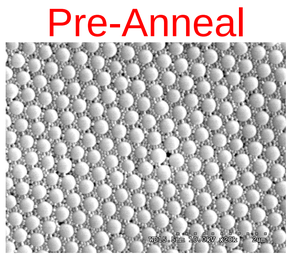


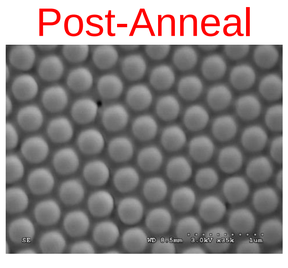


Blade Angle = 45°
Deposition Speed = 67 µm/s

400-nm SiO_2/75-nm PS

Top View Pre-Anneal | Top View Post-Anneal





Blade Angle = 45°
Deposition Speed = 87 µm/s

Conclusion

Monolayer arrays of SiO_2 were successfully realized at 500-nm and 400-nm. Sphere interstices were filled with smaller polystyrene spheres, which were then annealed at 140°C to form a microlens on the surface of the GaN-based light-emitting diode. For 500-nm SiO_2/75-nm PS, optimal deposition conditions were found to be a blade speed of 67 µm/s at an angle of 45° from the horizontal. For the 400-nm SiO_2/75-nm PS sample, the optimized deposition speed was found to be 87 µm/s, again at an angle of 45°. The emitted light from the diode was scattered at a greater angle than without the sphere array, resulting in a wider photon escape cone and a higher light extraction efficiency.

Future Works

Future works focused on increasing the light extraction efficiency of GaN-based light-emitting diodes using the rapid convective deposition method should explore the output light intensity of these enhanced devices at varying angles in three dimensions. Additional experimentation and optimization must be conducted on smaller SiO_2 nanosphere arrays, at diameter sizes such as 300-nm, 200-nm, and 100-nm.

References

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