Enhancement of light extraction efficiency of InGaN quantum wells light emitting diodes using SiO_2/polystyrene microlens arrays

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Improvement of light extraction efficiency of InGaN quantum wells light emitting diodes (LEDs) using SiO_2/polystyrene microspheres was demonstrated experimentally. The utilization of SiO_2/polystyrene microlens arrays on InGaN quantum wells LEDs, deposited via rapid convective deposition, allows the increase of the effective photon escape cone and reduction in the Fresnel reflection. Improvement of output power by 219% for InGaN quantum wells LEDs emitting at peak wavelength of 480 nm with SiO_2/polystyrene microspheres microlens arrays was demonstrated.
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The external quantum efficiency (η_{EQE}) of InGaN quantum wells (QWs) light-emitting diodes (LEDs),[1] depends on the injection efficiency (η_{inj}), radiative efficiency (η_{rad}), and light extraction efficiency ($\eta_{extraction}$). The low hole carrier mobility,[2] challenges in *p*-type doping,[3] and polarization-induced electric fields[4] impact the injection efficiency and radiative efficiency of the III-nitride LEDs. The large refractive index contrast at the GaN/air interface results in low light extraction efficiency.

Several approaches have been implemented to improve the light extraction efficiency of the InGaN QW LEDs, such as die shaping,[5,6] surface roughening,[7–9] photonic crystals,[10–12] nanopyramid,[13] sapphire microlenses,[14] and graded index-matched materials[15–17] approaches. The high cost of die shaping remains an important limitation. The disadvantage of surface roughening approach is related to the difficulty in controlling the process as well as achieving good repeatability of the roughness. The photonic crystal and nanopyramid approaches require very controlled dimensions utilizing e-beam lithography, which is not applicable for low-cost and large scale production. The use of graded index-matched materials had led to a reduced Fresnel reflection at the GaN/air interface, which in turn led to improvement in η_{EQE} by 28.4%.[15–17]

Here we present an InGaN quantum wells LEDs structure utilizing a SiO_2/polystyrene (PS) microlens array, resulting in significant enhancement of the light extraction efficiency from the top surface of the LEDs devices, as shown in Fig. 1. The implementation of SiO_2/PS microspheres leads to a low-cost and straightforward approach to form microlens arrays on top of the LEDs for improving light extraction efficiency, without using costly e-beam lithography process. The diameter of the microspheres can be controlled accurately from 0.1 to 2 μm,[18] resulting in good control and repeatability in the microlens structure and optical properties. This process also provides adequate adhesion to III-nitride materials at room temperature, and the materials are relatively transparent to visible light emission from the InGaN QWs. The deposition of two-dimensional (2D) close-packed SiO_2/PS colloidal crystal is also practical and straight forward, as compared to e-beam lithography or complex wafer fabrication techniques. As the SiO_2 microspheres are deposited as the final step on the top emission area of the LEDs, this approach avoids any degradation on the electrical characteristics of the LEDs.

In our approach, the SiO_2/PS microlens array was deposited on the top surface of the InGaN QW LEDs structure, as shown in Fig. 1. The refractive index of GaN in the visible spectrum is 2.5, while the refractive indices of PS and SiO_2 microspheres are 1.58 and 1.46, respectively. In this approach, the spherical SiO_2 microspheres with diameter of 1.0 μm are semiburied in the PS, thereby forming close-packed lenslike arrays. The use of these arrays on the top surface of the LEDs allows the photons emanating from the QW to scatter out from the LEDs structure with larger "effective" photon escape cone, thus leading to increase in the external quantum efficiency of the devices.

The photoluminescence (PL) and LEDs samples were grown using a vertical-type metalorganic chemical vapor deposition reactor. The PL samples were grown on a 3 μm *u*-GaN template on *c*-plane sapphire at a temperature of 1080 °C, employing a low temperature 30 nm *u*-GaN buffer layer. The PL structure was then grown on top of the *u*-GaN template. The active regions consist of four-period 2.5 nm InGaN QW and 12 nm GaN barriers, grown at a temperature of 710 °C. The In content of the InGaN QW of the PL

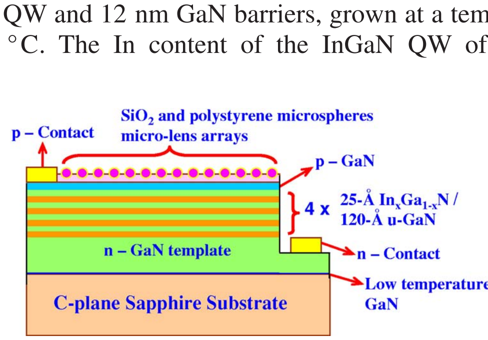

FIG. 1. (Color online) Schematic of InGaN QWs LEDs structure utilizing SiO_2/PS microspheres microlens array.

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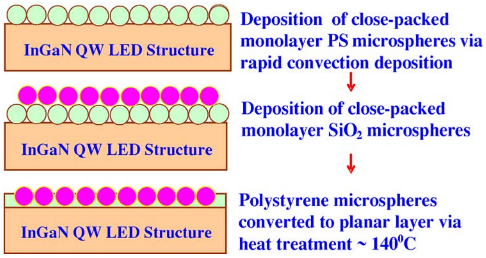


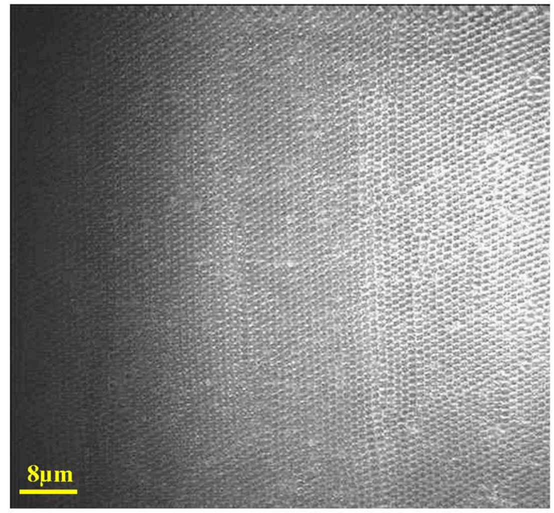
FIG. 2. (Color online) Process flow schematic of SiO_2/PS microspheres microlens arrays on InGaN QW LEDs samples via rapid convective deposition.

sample was found as 12%, as calibrated via x-ray diffraction.

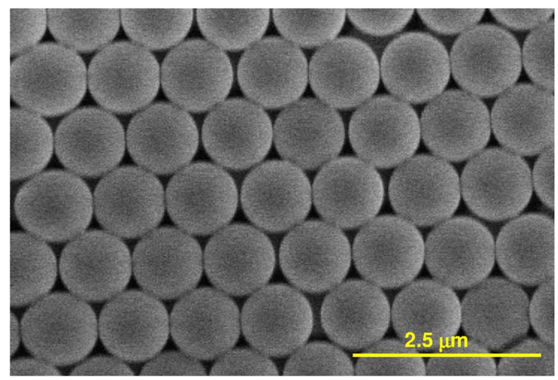
The *ex situ* rapid convective deposition[19] of the microsphere layers from colloidal suspensions were subsequently conducted on top of the InGaN QW PL and LEDs samples. The strategy behind using colloidal self-assembly is to exploit the tendency of monosized submicrometer spheres to spontaneously arrange into a close-packed 2D crystal. The strong capillary forces at a meniscus between a substrate and a colloidal suspension can induce crystallization of spheres into a 2D array.

The process flow of SiO_2/PS microlens arrays on the InGaN QW LEDs samples via rapid convective deposition is shown schematically in Fig. 2. The optimized volume fractions of the 1.0 μm diameter PS and SiO_2 microsphere suspension were 10% and 13%, respectively. A droplet volume of 10 μL PS colloid suspension was injected between the InGaN QW LEDs sample, and a deposition glass plate forming a wedge with the sample at an angle of $25° \pm 1°$. The glass plate is swept across the substrate at a speed of 45 μm/s by a linear motor. After depositing 1 ML of PS microspheres, the process was repeated to deposit 1 ML of SiO_2 microspheres. Finally, the coated samples were heated using a hotplate at 140 °C to melt the PS microspheres, thereby capturing the SiO_2 microspheres in a planar PS layer without significant rearrangements to the packing structure of the SiO_2. The SiO_2 microspheres are semiburied in the PS, forming hexagonal close-packed SiO_2/PS microlens arrays. Figures 3(a) and 3(b) show the confocal laser scanning microscopy and scanning electron microscopy images of the SiO_2/PS microlens arrays on top of the GaN layer of the LED structure, respectively. It is important to note that the optimized volume fractions of the PS and SiO_2 microspheres suspension as important factors in achieving the close-packed monolayer deposition process.

The PL comparison studies were conducted on $In_{0.12}Ga_{0.88}N$ QWs samples emitting with peak wavelength (λ_{peak}) at 419.3 nm. The PL measurements were conducted on samples (grown at the same time) with and without the microlens arrays, utilizing the He–Cd excitation laser ($\lambda = 325$ nm) from the backside of the samples at room temperature. The PL luminescence was collected from the top surface of the samples. Figure 4 shows the PL spectra of the $In_{0.12}Ga_{0.88}N$ QW PL samples with and without the microlens arrays. The PL luminescence peak intensity of the samples covered with microlens arrays exhibited 233.6% improvement over that of samples without microlens arrays. The integrated PL luminescence for samples with the microlens arrays also showed 269.7% improvement over that of the uncoated sample. Note that the multipeaked emission of the PL spectra for the uncoated sample is a well-understood artifact of the Fabry-Pérot cavity effect in the cavity formed by sapphire/GaN/air, resulting in interference effect. The existence of microlens arrays on the top surface of the sample scattered the emitted photons from the active media, resulting in suppression of the Fabry-Perot cavity effect.



(a)



(b)

FIG. 3. (Color online) (a) Confocal laser scanning microscopy and (b) scanning electron microscopy images of SiO_2/PS microlens array on top of InGaN QWs LED structure. The SiO_2/PS colloidal crystal forms 2D hexagonal closed-packed microlens arrays.

The SiO_2/PS microlens arrays were deposited on the LEDs device, employing 4 period of 2.2 ± 0.15 nm thick

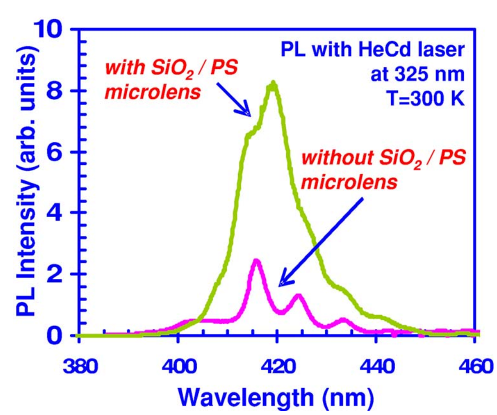


FIG. 4. (Color online) Comparison of photoluminescence intensity of $In_{0.12}Ga_{0.88}N$ QW samples with and without SiO_2/PS microlens array, with He–Cd excitation lasers ($\lambda \sim 325$ nm) at room temperature.

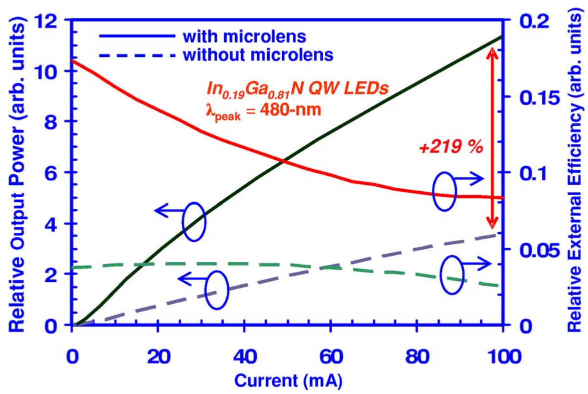


FIG. 5. (Color online) Comparison of relative light output power and external quantum efficiency vs injected current for $In_{0.19}Ga_{0.81}N$ QW LEDs with and without SiO_2/PS microlens array, emitting at $\lambda=480$ nm. The measurements were conducted under CW operation at room temperature.

(calibrated via transmission electron microscopy) $In_{0.19}Ga_{0.81}N$ QWs with GaN barriers, emitting with $\lambda_{peak}=480$ nm. The In content of the InGaN QW of the LEDs sample was found as $19\% \pm 1\%$, as calibrated via x-ray diffraction. The LEDs structure was grown on 3.0 μm *n*-GaN template on *c*-plane sapphire substrate. The *n*-GaN is Si-doped with *n*-doping level of 2×10^{18} cm^{-3}. The *p* GaN is grown utilizing 80 nm thick Mg-doped GaN (*p* doping$=3\times10^{17}$ cm^{-3}) at growth temperature of 970 °C, followed by N_2 annealing at a temperature of 780 °C for a duration of 5 min.

Continuous wave (cw) power measurements were performed at room temperature for LEDs devices with and without the SiO_2/PS microlens arrays. The on-wafer power measurement was done in a light proof dark chamber, using large-area planar-diffused silicon photodiode, and a benchtop optical power meter. Figure 5 shows the output power as a function of the driving current for up to 100 mA for both LEDs with an area of 1 mm^2. The cw power-current measurements exhibit 219% improvement in the output power of the LED device with SiO_2/PS microlens arrays at a current level of 100 mA, as compared to that without microlens arrays. The significant increase in the output power of the LEDs with microlens arrays can be attributed presumably due to the increase in its effective photon escape cone. In addition to the increase in its effective photon escape cone, the use of SiO_2 ($n=1.46$)/PS ($n=1.58$) as the intermediate refractive index materials for the microlens arrays also leads to reduced Fresnel reflection in the GaN/PS/SiO_2/air interface by as high as 4.7% for normal incidence, as compared to that for GaN/air interface. The Fresnel reflection for GaN/PS/SiO_2/air interface was calculated using transfer matrix propagation matrix method[20] for normal incidence.

The relative external quantum efficiency as a function of injection current of the LEDs can be obtained by differentiating the relative output power with the injection current. As shown in Fig. 5, there was an overall improvement in the relative external quantum efficiency of LEDs with SiO_2/PS microlens arrays as compared to that of the LEDs without the microlens arrays. At low current level ($I=5$ mA), the improvement of LEDs efficiency with microlens arrays was about 4.34 times. The improvement in the relative external quantum efficiency of 3.32 times is observed for LEDs with microlens at current level of 100 mA. This reduction in the improvement in LEDs with microlens arrays at high current level can be attributed to the thermal effect. The proof-of-concept experiments show promising results, and further understanding and optimization on the thermal distribution of the LEDs with microlens arrays are still required.

In summary, the enhancement of light extraction efficiency of InGaN QW LEDs by using SiO_2/PS microlens arrays was demonstrated. The utilization of SiO_2/PS microspheres deposited via rapid convective deposition[19] on InGaN QW PL sample led to improvement of 233.6% and 269.7% for its peak luminescence intensity ($\lambda_{peak}=419.3$ nm) and integrated luminescence, respectively. Improvement of output power by 219% (at current level of 100 mA) for the electrically injected InGaN QW LEDs emitting with $\lambda_{peak}=480$ nm with microlens arrays was also obtained, presumably due to the increase in the effective photon escape cone and reduced Fresnel reflection. The utilization of this low-cost and controllable microsphere deposition process allows a practical approach for enhancing the light extraction efficiency of InGaN QW LEDs.

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