High Efficiency Light Emitting Diodes with Nanostructured Surfaces

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Abstract:

Low extraction efficiency is one of the major obstacles preventing a more widespread use of light emitting diodes (LEDs) for solid-state lighting. Previous efforts to increase LED extraction efficiency through surface texturing have proven effective, but they require additional *ex situ* processing steps after material growth. We have developed an inexpensive, simple, and effective method of nanoscale surface texturing for gallium nitride (GaN) LEDs, which can be performed *in situ*, directly after the material growth, using standard tools. We compare ordinary planar GaN LEDs to surface textured GaN LEDs, in order to demonstrate the effectiveness of this method. Our devices are characterized by photoluminescence and electroluminescence techniques, which include optical intensity vs. current, and current vs. voltage characteristics. We aim to improve LED extraction efficiency by at least a factor of two.

Introduction:

Light emitting diodes (LEDs) are promising semiconductor devices for solid state lighting. Due to their high capacity to produce photons, they could potentially replace inefficient fluorescent and incandescent lighting. However, state-of-the-art LEDs are far from reaching the required level of efficiency. One major obstacle is the low extraction efficiency due to total internal reflection. Most of the photons generated in the active region are reflected off of the device's surface and cannot escape the device. A typical GaN light emitting diode has extraction efficiency as low as 4% [1].

Surface texturing has proven to be an effective method of increasing LED extraction efficiency. Prior approaches use either random photoelectrochemical etching [2] or a patterned photonic crystal grid [3]. Both methods require additional *ex situ* processing steps after material growth, costing extra time and money. We have developed a new *in situ* technique of surface texturing that can be integrated with the material growth and requires no additional *ex situ* processing. Therefore, it can be a much more practical option for implementation in the LED industry.

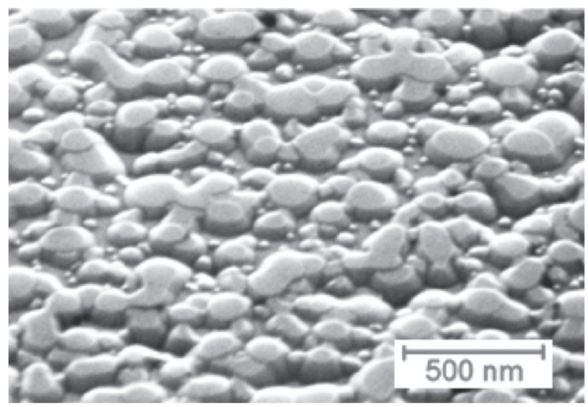

Figure 1: SEM image of the ISST surface (300 sec). Notice that most of the features are smaller than 100 nm.

Experimental Procedure:

Our goal was to compare planar LEDs to surface textured LEDs, in order to demonstrate the effectiveness of our new method of surface texturing. Our GaN devices were grown by metal-organic chemical vapor deposition (MOCVD). Immediately following the material growth, we exposed the sample surface with silane, while maintaining an ammonia over-pressure, which prevented the unintentional decomposition of GaN from the surface. This *in situ* silane treatment (ISST) roughened the LED surface, producing random nanoscale textured features (Figure 1). It took

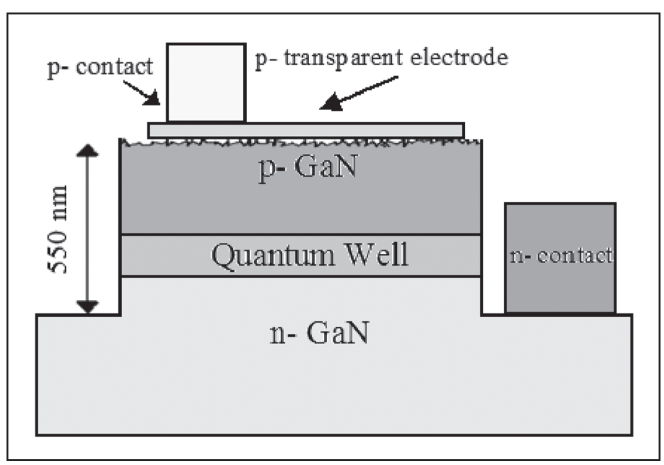

Figure 2: Cross-sectional view of our processed LED.

less than ten minutes to perform, required only standard tools and no *ex situ* processing. The photoluminescence characterization of our samples revealed that ISST increased the photoluminescence (PL) intensity by a factor of two. Such promising results provided sufficient motivation for us to begin processing the samples to produce electrical devices.

The processing of the electrical LEDs with ISST induced surface-textures is as follows. We first deposited the p-transparent electrode (Figure 2), made of Ni and Au, using photolithography and thin film evaporation. The p-transparent electrode was only 10 nm thick, thin enough to allow light to pass through. Then, we used rapid thermal annealing to enhance the contact between the p-transparent electrode and the LED surface. Next, we used reactive ion etching to etch 550 nm down to the n-type GaN, creating a mesa. This allowed us to place a Ti/Au n-contact on the n-type GaN. Finally, we deposited a gold p-contact on the p-transparent electrode. We tested our devices using a pulsed current source. The pulsed current was used to avoid the excessive heating of the device, allowing us to inject higher currents into the device without active cooling.

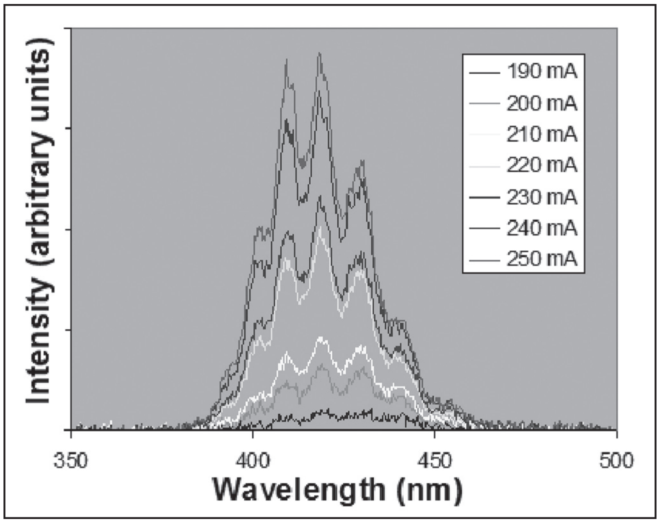

Figure 3: Electroluminescence emission spectrum for ISST.

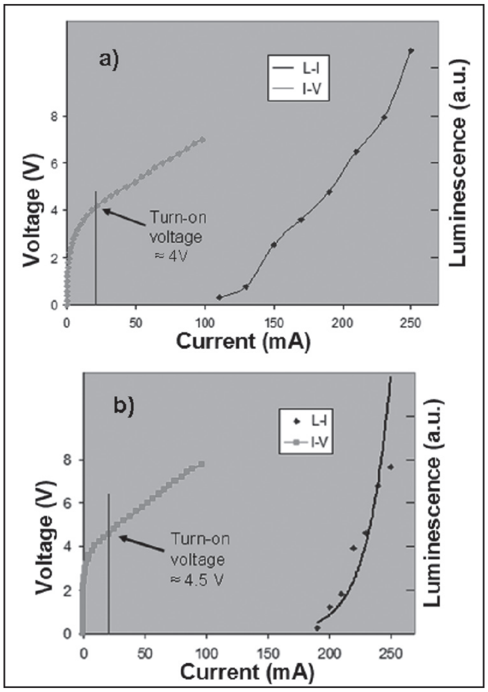

Figure 4: L-I and V-I for:
a) planar LED; b) ISST LED.

Results:

One of the issues that our project addressed is the difficulty of placing an electrical contact on a textured surface. The ISST surface was suitable for placement of the p-transparent electrode because the textured features are very small (< 100 nm wide and < 10 nm tall). We demonstrated electroluminescence in our ISST sample (Figure 3), which indicated that there was electrical contact between the p-electrode and the textured surface. However, the contact has not been optimized, so we were unable to make a direct comparison between the planar and ISST samples at this point.

The current vs. voltage and optical intensity vs. current characteristics of our devices (Figure 4) illustrated the problems with the p-electrode. The ISST sample had a higher turn-on voltage than the planar sample. Therefore, the ISST sample had a higher resistance, probably due to un-optimized contact between the p-electrode and the textured surface. The L-I curve for the ISST sample was much steeper than for the planar sample, which also indicated poor electrical contact.

Conclusion:

We have developed GaN LEDs, using our ISST method to produce nanoscale surface textures. This method is simple and cost effective, and could easily be implemented in the LED industry. Photoluminescence characterization showed an improvement in extraction efficiency by a factor of two compared to planar devices. We fabricated electrical devices, and demonstrated electroluminescence in ISST samples. However, p-contact resistance still needs to be optimized before we can compare ISST devices to planar devices.

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References:

[1] Schubert, E.; Light Emitting Diodes; Cambridge Univ. Press; 2006.

[2] Wierer, J. et al.; "InGaN/GaN quantum-well heterostructure light-emitting diodes employing photonic crystal structures"; Applied Physics Letters, Volume 84 Number 19, 3885 (2004).

[3] Fujii, T. et al.; "Increase in the extraction efficiency of GaN-based light-emitting diodes via surface roughening"; Applied Physics Letters, Volume 84 Number 6, 855 (2004).