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# InGaN Nanorod LEDs: A Performance Assessment

*(Invited Paper)*

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***Abstract*—Light Emitting Diodes (LEDs) have become an attractive concept as efficient light sources. In this contribution, the electro-optical performance of III-nitride based core-shell nanorod LEDs is investigated by detailed simulation. In contrast to their planar counterparts, they possess increased active region area on small footprint, non-polar active regions with c-plane vertical growth, and form horizontal two-dimensional active photonic crystals for the optical extraction process.**

## I. INTRODUCTION

III-nitride based light emitting diodes (LEDs) have become powerful and efficient light sources for various lighting applications, with internal quantum efficiencies larger than 80%. Despite their success, they are still plagued by relatively high chip cost and a drop in efficiency at high current operation [1]. Although the root cause of efficiency droop hasn't been clarified yet, it is believed to be an intrinsic electronic effect of the active region [2].

One approach to solve these issues is the use of nanorod LEDs with the pn-junction arranged in vertical direction along the rod. These core-shell type devices can be grown on silicon substrates, and due to their large aspect ratio, can achieve a pn-junction area which is a multiple of the respective substrate area [3]. This allows LED operation at lower current densities, where the efficiency is high, and the droop effect does not occur. In this contribution, a comprehensive analysis of the core-shell nanorod device concept is presented, based on simulation. Both optical and electronic aspects are discussed.

## II. DESIGN BASICS

Figure 1 shows the basic arrangement of a core-shell nanorod, with the c-axis of the wurtzite crystal aligned in vertical direction. In some implementations, the pn-junction and active region extends over the sidewalls as well as on the top in horizontal direction (as shown). Optionally, the top active region can be removed or avoided so that only the sidewall active region is present.

While in a planar LED the active area is identical to the wafer area, the core-shell nanorod LED features an active area increase (in radial approximation) of

$$m = \frac{A_{rod}}{A_{planar}} = f * \left(\frac{d}{D}\right)^2 * \left(1 + \frac{4h}{d}\right) \tag{1}$$

with $f = \frac{D^2}{a^2}$ being the area fill factor, and the other variables described in fig. 1.

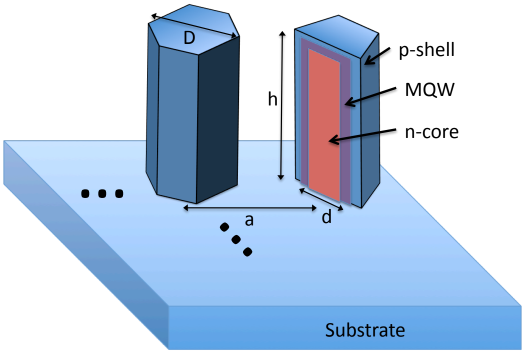

Fig. 1: Device geometry of a core-shell III-nitride nanowire. The multiple quantum-well (MQW) region includes an electron blocking layer (EBL).

Fig. 2 gives the active area enhancement for some exemplary cases of nanorod dimensions which are realistic to achieve with available technology. An enhancement of approx. 10 is feasible, which translates into a reduced local current density if the LED is operated at the same current. The internal efficiency curve shows less droop at lower current.

## III. SIMULATION RESULTS

### A. Current Injection Efficiency

Homogeneous carrier injection in the active region of the high aspect ratio nanorods is a crucial requirement in order to fully benefit from the area enhancement of the rod

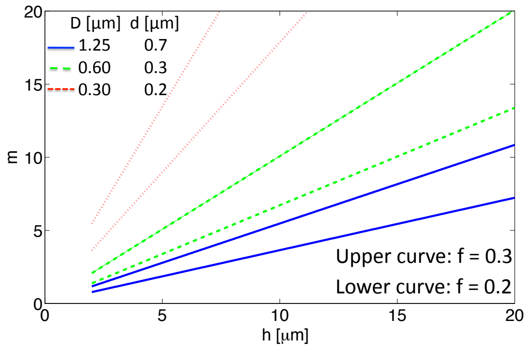

Fig. 2: Active area enhancement of core-shell nanorod LED compared to planar LED for different fill-factors $f$ and rod height $h$.

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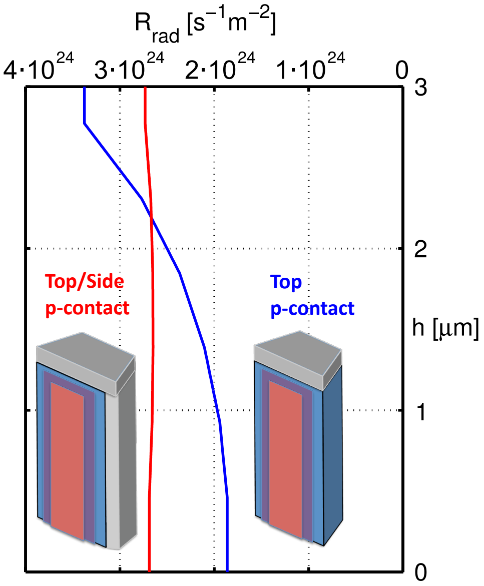

Fig. 3: Radiative recombination rate in MQW core-shell nanorod LED at a typical operating current density (I= $3.5 \times 10^{-6}$A).

arrangement. The main limiting factor is the thin p-doped shell, as the hole mobility in GaN is low. If the rod shell is contacted on top, and on bottom for the core, the active carrier density, and therefore radiative recombination rate, decreases towards the bottom of the rod . In contrast, a transparent p-contact that covers the entire sidewall gives optimum injection efficiency. Using microscopic carrier transport models, this problem can be studied in detail [4]. Fig. 3 shows a plot of the radiative recombination rate in the vertical cross-section through the quantum-well, at a typical LED operating current. The simulation is a 2-dimensional drift-diffusion model with inclusion of quantum transport [5]. The rod dimensions are $D = 1.25\mu$m, $d = 0.7\mu$m, and $h = 3\mu$m.

The n-contact is on the bottom of the rod, and two scenarios for the top contact are investigated. The red curve corresponds to the case where the entire p-shell is contacted by a transparent material; the blue curve shows an LED with a top contact only. Clearly, the thin p-shell creates a hole injection bottleneck, so that the radiative recombination decreases by almost 50%.

### *B. Optical Properties*

Several specifics of the nanorod geometry need to be considered for the optical analysis. First, the vertical MQW active region is grown on a non-polar crystal orientation. Therefore, the active region consists of non-polar QWs without the interface piezo-polarization. This leads to a polarized optical emission, and to a higher re-absorption compared to c-plane quantum-wells [4]. The polarization of the optical emission results in a predominantly vertically directed emission (approx. 70% of emitted power in the dipole oriented in horizontal direction), which is beneficial for device operation.

The optical extraction efficiency depends on the electromagnetic properties of the nanorod array. A single nanorod can act as dielectric waveguide, and a bottom reflector increases the vertical outcoupling efficiency. As the rods can be arranged in a periodic pattern, photonic crystal effects can be exploited in the design [6]. The in-plane radiation can be suppressed by a photonic band gap, which, in the case of low internal efficiency cases, can improve the external efficiency. However, photonic band gaps also can suppress radiation with non-zero vertical wave vector, which contributes to the output power. Detailed electromagnetic simulations have been performed in order to analyze this non-trivial problem [7], which have shown operation outside of the band gap shows highest extraction efficiency. Also, transparent electrical contacts on the sidewalls are required, which are optical absorbers and limit the extraction efficiency.

## IV. CONCLUSION

Nanorod LEDs offer conceptual advantages over traditional in-plane designs, such as enhanced active pn-area on a given substrate real estate, substrate material flexibility, non-polar active regions, and intrinsic photonic crystal filters. In order to benefit from these features, careful choice of the rod geometry and arrangement need to be done, which can be supported by detailed simulation. As a result, LEDs with reduced droop in efficiency can be designed.

## ACKNOWLEDGMENT

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## REFERENCES

[1] M. R. Krames, O. B. Shchekin, R. Mueller-mach, G. O. Mueller, L. Zhou, G. Harbers, and M. G. Craford, “Status and Future of High-Power Light-Emitting Diodes for Solid-State Lighting,” *IEEE Journal of Display Technology*, vol. 3, no. 2, pp. 160–175, 2007.

[2] J. Piprek, “Efficiency droop in nitride-based light-emitting diodes,” *physica status solidi (a)*, vol. 207, no. 10, pp. 2217–2225, 2010.

[3] S. Li and A. Waag, “GaN based nanorods for solid state lighting,” *Journal of Applied Physics*, vol. 111, no. 7, p. 071101, 2012. [Online]. Available: http://link.aip.org/link/?JAP/111/071101/1

[4] F. Römer, M. Deppner, Z. Andreev, C. Kölper, M. Sabathil, M. Straßburg, J. Ledig, S. Li, A. Waag, and B. Witzigmann, “Luminescence and Efficiency Optimization of InGaN/GaN Core-Shell Nanowire LEDs by Numerical Modelling,” *SPIE Proceedings, Photonics West*, 2012.

[5] S. Steiger, R. Veprek, and B. Witzigmann, “Unified simulation of transport and luminescence in optoelectronic nanostructures,” in *Journal of Computational Electronics*, 2008, pp. 509–520.

[6] S. Fan, P. R. Villeneuve, J. D. Joannopoulos, and E. Schubert, “High Extraction Efficiency of Spontaneous Emission from Slabs of Photonic Crystals,” *Physical Review Letters*, vol. 78, no. 17, pp. 3294–3297, 1997.

[7] C. Kölper, M. Sabathil, B. Witzigmann, F. Römer, W. Bergbauer, and S. M., “Optical properties of individual GaN nanorods for light emitting diodes: Influence of geometry, materials and facets,” *SPIE Proceedings, Photonics West*, 2011.