Photonic Crystals for Improved InGaN LED Efficiency

by **A. J. Fischer, J. R. Wendt, J. J. Wierer[1], M. R Krames[1], D. Li[2], S. R. J. Brueck[2], R. J. Shul, S. H. Kravitz, K. W. Fullmer, and C. F. Schmidt**

Motivation—Light Emitting Diodes (LEDs) based on InGaN will be used in future high efficiency lighting applications. Currently available semiconductor-based white light emitters, which are based on InGaN LEDs, have efficiencies better than incandescent light bulbs, but still much lower than fluorescent tubes. The efficiency is limited by poor internal quantum efficiency as well as poor light extraction efficiency. Photonic crystals offer a potential solution to both of these problems. Internal quantum efficiency can be enhanced via the Purcell effect where the radiative recombination rate is increased by placing the quantum well emitters inside an optical cavity. At the same time, a photonic crystal can be used to improve light extraction by diffracting waveguided modes out of the semiconductor.

Accomplishment—In addition to problems associated with low internal quantum efficiency, InGaN LEDs are limited by the extraction of light from the high index semiconductor chip. Light is generated inside of the semiconductor and bounces around due to total internal reflection. There is a high probability that the light will be absorbed before it can escape from the semiconductor. Figure 1 shows a schematic diagram of a photonic crystal LED. For typical InGaN LEDs, a large fraction of the light is emitted into waveguided modes internal to the semiconductor rather than into radiation modes. By incorporating a photonic crystal into an InGaN LED these waveguided modes can be extracted improving the total device efficiency.

Fabrication of photonic crystals in GaN is complicated by the difficulty of etching GaN, which is extremely hard and chemically inert. Photonic crystals are fabricated by dry-etching GaN using a Cl-based plasma. Submicron patterning is performed using e-beam, interferometric, or nano-imprint lithography. Figure 2 shows a focused-ion-beam scanning electron microscope (FIB-SEM) image of a photonic lattice etched into GaN. The photonic lattice pattern shown here is a triangular lattice with a pitch of 205nm and a hole diameter and depth of 110nm and 380nm, respectively. The straight sidewalls and high aspect ratio (depth to width) of greater than 3:1 are very desirable features for efficient light extraction.

Photonic crystal LEDs have been fabricated by combining LED processing and photonic crystal processing to make an electrically-injected InGaN LED. Figure 3 shows the far field emission patterns for a photonic crystal LED compared to a control LED with no photonic crystal. The photonic crystal LED shows a strongly modified far field pattern with a triangular symmetry. This pattern is due to the extraction of waveguided modes. InGaN LEDs with photonic crystals showed a 1.5X increase in efficiency compared to control LEDs.

Significance—Many InGaN LED performance improvements are still required including increased efficiencies, higher power lamps, and lower cost per lamp. Photonic crystals have the potential to dramatically increase InGaN LED efficiency. This work is a first step towards improving the efficiency of InGaN LEDs such that white light efficacies of 200 lm/W will become a reality.

[1]Lumileds Lighting, [2]University of New Mexico

Sponsors for various phases of this work include: Laboratory Directed Research & Development and DOE Office of Energy Efficiency and Renewable Energy (EERE)

Contact: Arthur J. Fischer, Advanced Materials Sciences, Dept. 1123
Phone: (505) 844-6543, Fax: (505) 844-3211, E-mail: ajfisch@sandia.gov

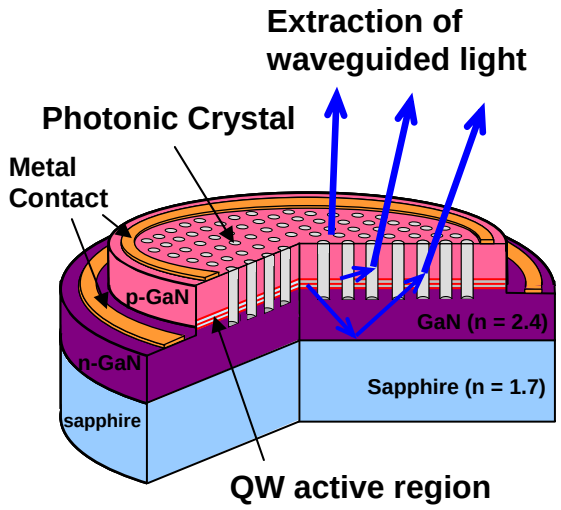

Figure 1. Schematic diagram of an InGaN photonic crystal light emitting diode.

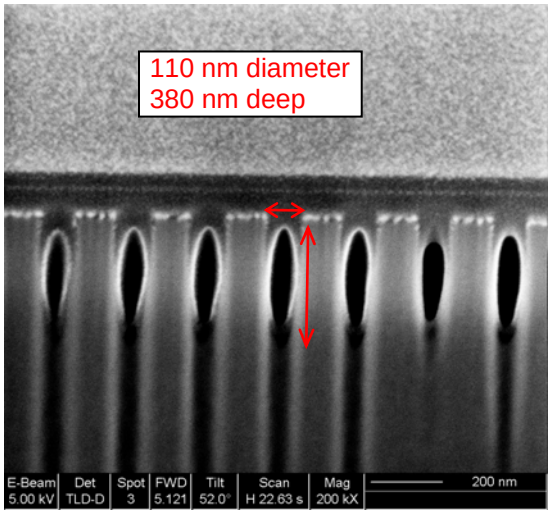

Figure 2. Focused ion-beam scanning electron microscope image of a photonic crystal etched in GaN. This photonic crystal has a lattice constant of 205nm.

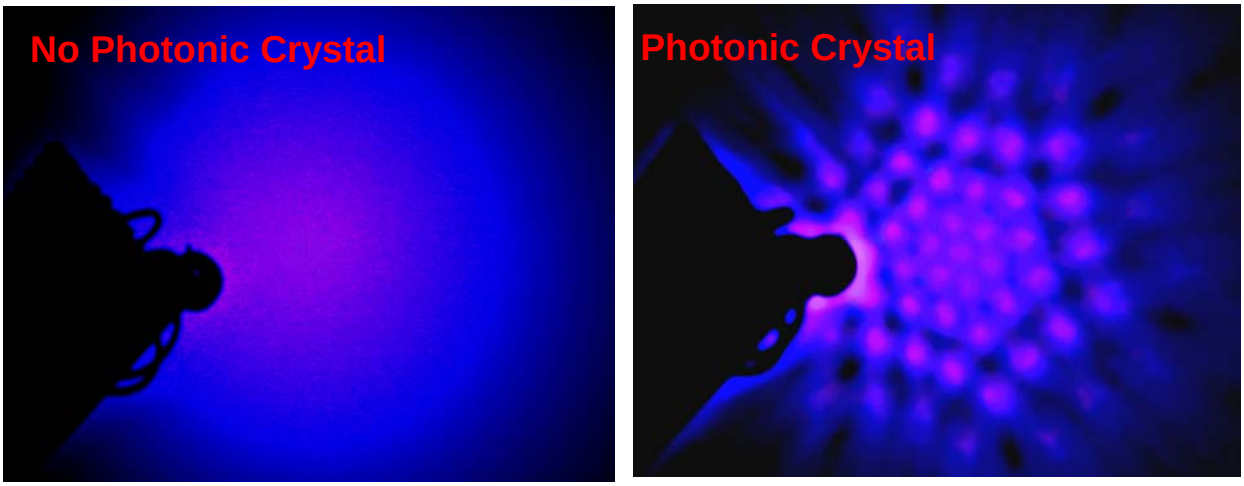

Figure 3. Far field emission patterns from a photonic crystal light emitting diode (LED) and a control sample with no photonic crystal. The photonic crystal LED has a strongly modified emission pattern due to scattering of waveguides modes out of the LED chip.