Optimization of Indium Incorporation in InGaN Multi-Quantum Wells

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Motivation—Light-emitting diodes (LEDs) are poised to replace traditional incandescent and fluorescent lights by virtue of their potential for more energy-efficient generation of white light. The most efficient solid-state white-lighting sources will combine red, blue, and green LEDs. While efficient red and blue LEDs exist, high-efficiency green LEDs have proven difficult to produce using the alloys of either AlInGaP, or more recently, InGaN.

Two major issues limit the structural quality and light-emitting efficiency of InGaN/GaN materials presently grown by MOCVD. First, lower growth temperatures must be used to incorporate the higher indium compositions needed for deep-green emitters. Second, as the composition increases, the lattice-mismatch strain of InGaN epitaxy on GaN also increases. Lower growth temperatures combine with higher InGaN strains to cause a variety of materials defects and nanostructures as these alloys push towards green. The present research seeks to understand both the mechanisms leading to defect formation and the impact of these defects on luminescent efficiency.

Accomplishment—Recent work has focused on the successful installation of a new Veeco D-125 MOCVD reactor and subsequent optimization of this reactor to grow state-of-the-art InGaN materials for fundamental studies of luminescence. Optimization studies have examined the influence of growth parameters such as temperature, pressure, growth rate, precursor flow, and carrier-gas flow on both indium incorporation and attendant materials defects. These studies have led to Sandia's first multi-milliwatt blue LEDs and Sandia's first green LEDs emitting near 515 nm.

Structural and optical feedback for these studies was provided by x-ray diffraction (XRD), atomic-force microscopy, Nomarski optical microscopy, photoluminescence spectroscopy (PL), and electroluminescence quick tests. Figure 1 shows typical XRD data for a multi-quantum well (MQW) that emits blue-green light at 490 nm. The MQW structure was evaluated using dynamical diffraction simulations of the measured XRD rocking curve. The excellent agreement between simulation and experiment indicates the presence of a structurally coherent MQW superlattice containing few v-defects, indium-metal inclusions, or misfit dislocations. Figure 2 shows the PL-emission wavelengths observed for various MQW samples grown during our studies. As indium composition increases, the redshift of the MQW emission relative to the bulk bandgap also increases. Since indium compositions beyond ~20% are difficult to obtain, this well-width-tunable redshift is crucial for reaching deep-green wavelengths. The redshift results from piezoelectric Stark shifts and InGaN-alloy compositional fluctuations that are the subject of ongoing studies. Finally, Fig. 3 shows the dramatic effect of epitaxial strain on indium incorporation. While coherent InGaN layers are indeed limited to ~20% indium, strain-relaxed layers readily incorporate up to 40% indium. Thus, efficient green LEDs may require improved substrates with a better lattice match to InGaN.

Significance—Our research program is providing the fundamental knowledge needed to make energy-efficient solid-state white lighting a practical reality. Such a reality could ultimately reduce American energy expenditures for lighting by as much as $30 billion/year.

Sponsors for various phases of this work include: DOE Office of Basic Energy Sciences and Laboratory Directed Research & Development

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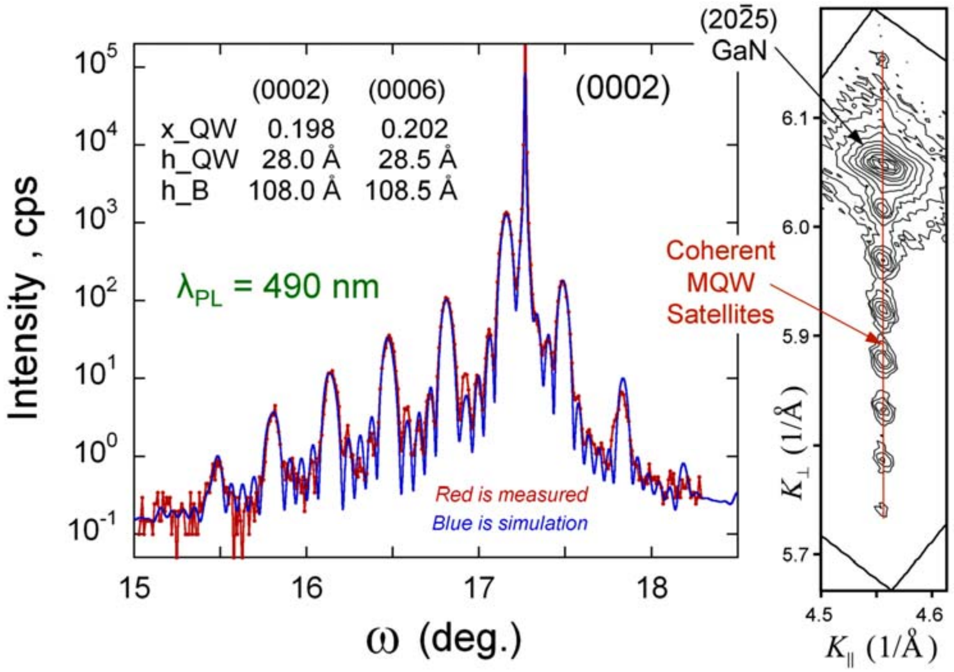

Figure 1. XRD analysis of a 5-period InGaN/GaN MQW grown on GaN/sapphire. Using dynamical x-ray diffraction theory, we simulated the (0002) rocking-curve data and found that the MQW consists of 28 Å thick $In_{0.20}Ga_{0.80}N$ wells and 108 Å thick GaN barriers; (0006) data confirm the (0002) results. The (20-25) reciprocal space map at the right demonstrates that the MQWs are coherently strained to the underlying GaN lattice, as assumed in the simulations.

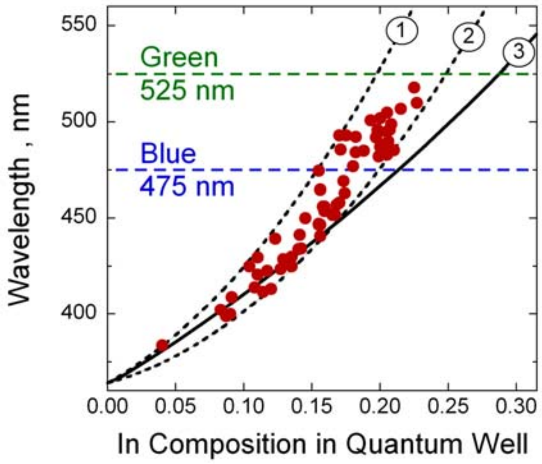

Figure 2. PL measurements of MQW-emission wavelength vs. MQW composition. Lines 1 and 2 bound the measurements; line 3 shows the emission wavelengths of bulk InGaN alloys. As In content rises, piezoelectric Stark shifts and compositional fluctuations also rise, which causes the MQW emission to redshift.

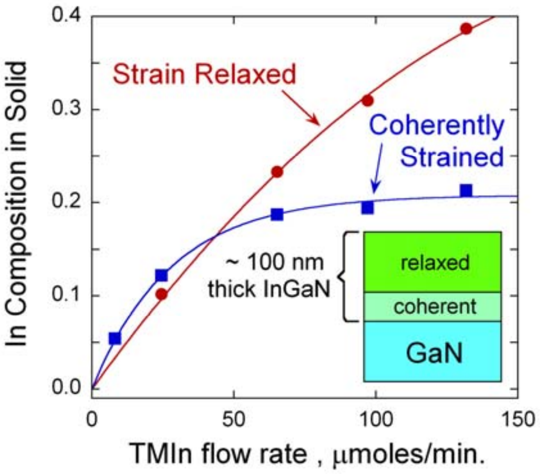

Figure 3. XRD measurements of the composition of 100 nm thick InGaN films grown on GaN at 760 °C. Initially coherent $In_xGa_{1-x}N$ films are limited to x=0.20 at high TMIn flow rates. Strain relaxation occurs as the film grows thicker, which yields a second layer with much greater In content at the same high flow rates.