Enhanced Luminescence of InGaN Quantum Wells Grown on InGaN Underlayers

by **M. H. Crawford, D. D. Koleske, S. R. Lee, N. A. Missert, D. M. Follstaedt, and K. H. A. Bogart**

Motivation—The luminescence efficiency of InGaN quantum well (QW) structures depends on a number of factors that are not well understood. Recently, a dramatic enhancement of the luminescence efficiency of InGaN QWs has been observed with the addition of a lower-growth-temperature $In_xGa_{1-x}N$ epilayer between the QWs and the higher-growth-temperature GaN template layer (Fig. 1a). The focus of this work is to elucidate the mechanisms that drive this luminescence enhancement.

Accomplishment—Several hypotheses have been tendered to explain the impact of underlayers on luminescence; we focus here on two prominent examples. First, it has been proposed that underlayers reduce the density of nonradiative recombination centers [Akasaka, *et al*., APL (2005); Son, *et al.,* Journal of Crystal Growth (2006)]. Second, the low growth temperatures of InGaN underlayers contribute to the formation of hexagonal pit defects ("V-defects") that decorate threading dislocations. Both Takahashi, *et al.* (JJAP (2000) and Hangleiter, *et al.* (PRL (2005) have proposed a novel screening mechanism related to such V-defects that could lead to luminescence enhancement. In the case of Hangleiter, *et al.*, QWs on the inclined facets of V-defects (Fig. 1b) are shown to be thinner, of lower indium composition, and therefore of higher bandgap than basal plane QWs. Thus, V-defects may enable an energy barrier around threading dislocations, preventing carrier capture and nonradiative recombination.

To evaluate these hypotheses, we have grown a number of different blue-emitting InGaN QW-on-underlayer samples and have evaluated their optical and structural properties. Temperature-dependent photoluminescence (PL) shows that QW internal quantum efficiency (IQE) indeed rises when V-defect-containing underlayers are added underneath the QWs (Fig. 1c). The increase in IQE varies from ~2X up to a remarkable ~18X and depends on the underlayer thickness, composition, and layer sequence – even though similar V-defects are present in all samples. To confirm the surprisingly non-dominant behavior of the V-defects, we developed underlayers of similar composition and thickness, but either *with* (Fig. 2a) or *without* (Fig. 2b) V-defects through control of underlayer growth temperature. Comparing the temperature-dependent PL of QWs on these two underlayers with the PL of QWs grown without an underlayer, we see that V-defects actually have *no influence* on the improved IQE (Fig. 2c), refuting the recent V-defect models. We instead see a critical dependence on the presence of indium in the underlayer (Fig. 1c). In addition, scanning cathodoluminescence images (not shown) reveal that the *increase* of luminescence with the addition of indium to the underlayers is relatively uniform across the samples, with no clear spatial correlation to V-defects. These characteristics support a model whereby indium containing underlayers reduce nonradiative centers associated with an underlying point-defect or impurity population.

Significance—With direct bandgaps that span the entire visible spectrum, InGaN semiconductor alloys have tremendous potential as efficient light-emitters for solid-state white lighting. The present studies on luminescence mechanisms help provide the fundamental knowledge needed to make this revolutionary, energy-efficient technology a practical reality.

Sponsors for various phases of this work include: Laboratory Directed Research & Development/National Institute for Nano Engineering (NINE) and DOE Office of Basic Energy Sciences

Contact: Mary H. Crawford, Semiconductor Material & Device Sciences, Dept. 1123
Phone: (505) 284-9380, Fax: (505) 844-3211, E-mail: mhcrawf@sandia.gov

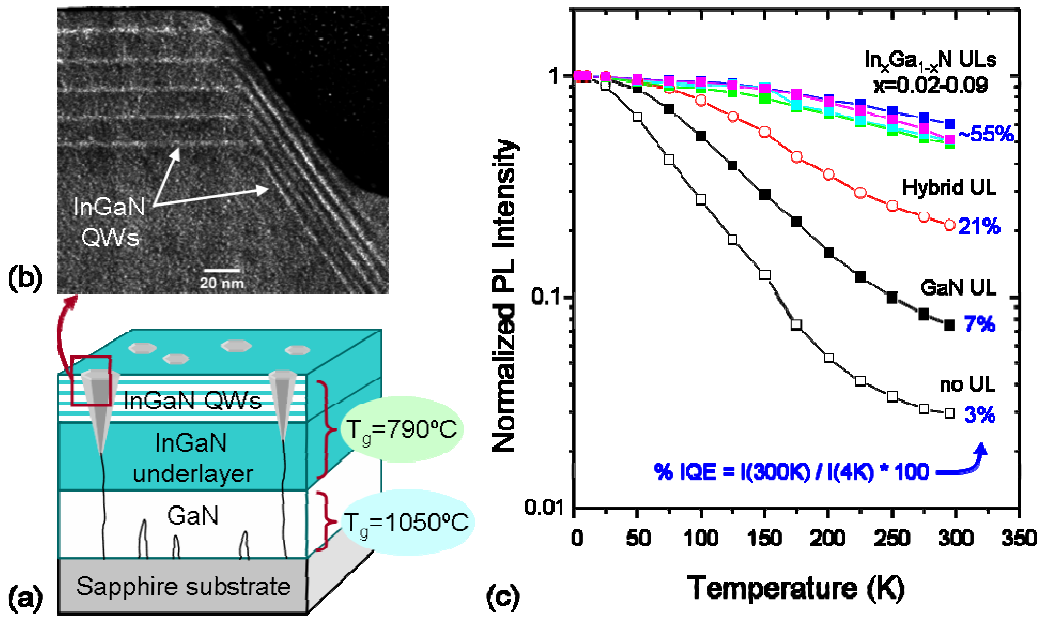

Figure 1. (a) Schematic diagram of an InGaN QW structure with an InGaN underlayer; (b) Z-contrast STEM image of the upper corner of a V-defect showing InGaN QWs on the inclined facets of the V-defect pit; (c) temperature-dependent photoluminescence of blue-emitting InGaN QWs grown on 200-nm-thick underlayers of varying indium composition. The hybrid underlayer (UL) is a 180-nm-thick GaN/ 20-nm-thick $In_{0.02}Ga_{0.98}N$ bilayer. Internal quantum efficiency (IQE) is defined as the ratio of integrated PL intensity at 300K and 4K. All underlayers shown are grown at 790 ºC and have V-defects decorating threading dislocations.

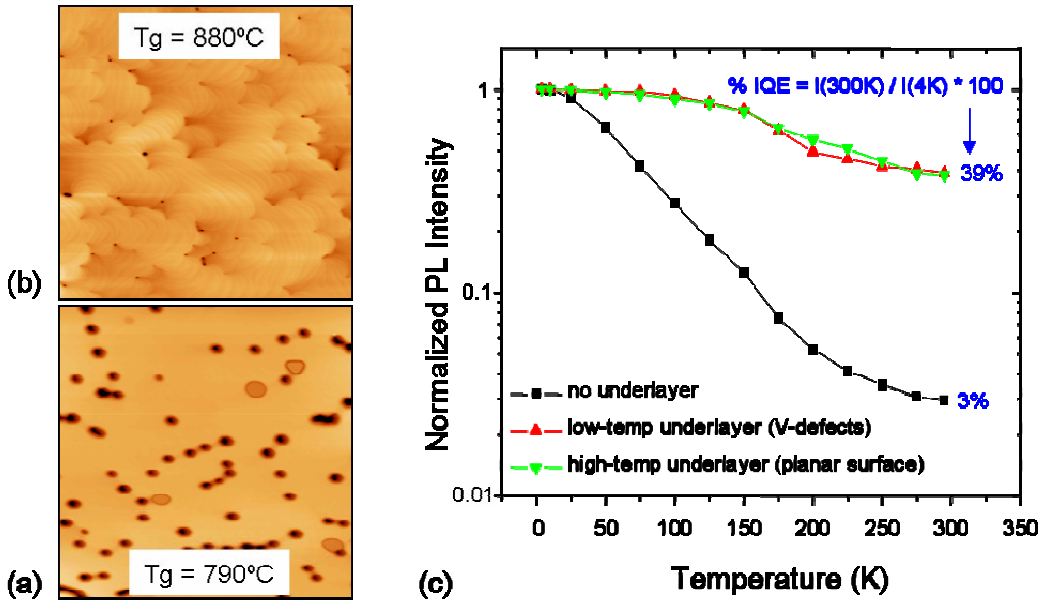

Figure 2. 3 µm x 3 µm atomic force microscopy (AFM) images of 200-nm-thick $In_{0.02}Ga_{0.98}N$ underlayers grown at (a) 790 ºC to induce V-defect formation, or at (b) 880 ºC to induce a more planar surface with no V-defects; (c) temperature-dependent photoluminescence of blue-emitting InGaN QWs grown on these underlayers compared to QWs grown directly on high-temperature-grown GaN without an underlayer.