Indium-induced Step Transformation during InGaN Quantum-well Growth on GaN

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Motivation—LEDs fabricated from the group-III nitrides are surprisingly bright despite the fact that they contain high dislocation density. Several theories have been proposed to explain the efficient light emission. These theories require some form of spatially distributed energy minima that localize carriers away from non-radiative recombination centers located at dislocations; however, definitive proof for one given theory over another is still lacking. The importance of localization and the extent to which it can be manipulated to further improve light efficacy are intriguing questions.

Accomplishment—One theory proposes that InGaN-quantum-well (QW) thickness fluctuations couple to piezoelectric-fields in the QWs, thereby producing energetic fluctuations strong enough to spatially localize carriers. These QW thickness fluctuations have been observed in high-resolution TEM images, lending credence to this theory.

Recently, we have found that these thickness variations can arise naturally through changes in the structure of surface steps during InGaN growth on GaN. Figure 1 shows examples of this morphology change for single- and double-QW heterostructures. Image (a) shows an AFM of the starting GaN step structure, which is dominated by single-layer steps. Images (b) and (c) show the increase in multiple-layer steps after the growth of single $In_{0.10}Ga_{0.90}N$ and $In_{0.20}Ga_{0.80}N$ QWs. The notably greater texturing of $In_{0.20}Ga_{0.80}N$ QWs indicates that the driving force for this transformation likely depends on indium concentration in the QW. Image (d) shows a double $In_{0.20}Ga_{0.80}N$ QW structure, which has a similar step structure to the single $In_{0.20}Ga_{0.80}N$ QW in image (c). The key result is that reduced growth temperature, which is required for indium incorporation, does not act alone to alter the GaN step structure, but concomitant addition of indium to the growth does.

Figure 2 further quantifies the change in step structure as the number of $In_{0.20}Ga_{0.80}N$ QWs increases. The figure reveals two notable observations. First, the frequency of single-layer steps decreases and the frequency of multiple-layer steps increases. Second, the step-height frequencies stop changing for heterostructures containing more than two QWs, suggesting that the mechanisms that roughen and smooth the multi-QW structures are balanced by each other. In other experiments, we found that the degree of multiple-layer step evolution depends on the amount of indium incorporated into the QWs. We speculate that the InGaN roughens in an attempt to reduce the stress of the InGaN layer. Although more evidence is required, this roughened InGaN step configuration might be essential to nitride-based LED brightness by providing QW thickness fluctuations sufficient to localize the electron-hole pairs.

Significance—Although the mechanism of the electron-hole localization is not yet well understood, this research aims to investigate morphological influences on overall luminescence efficiency. As shown here, this morphology evolves naturally during InGaN growth on GaN. If this morphology influences the localization, it may explain the reason single InGaN QWs typically do not show appreciable luminescence, while multiple QWs do. Additional research is underway to correlate the InGaN morphology to the luminescence efficiency.

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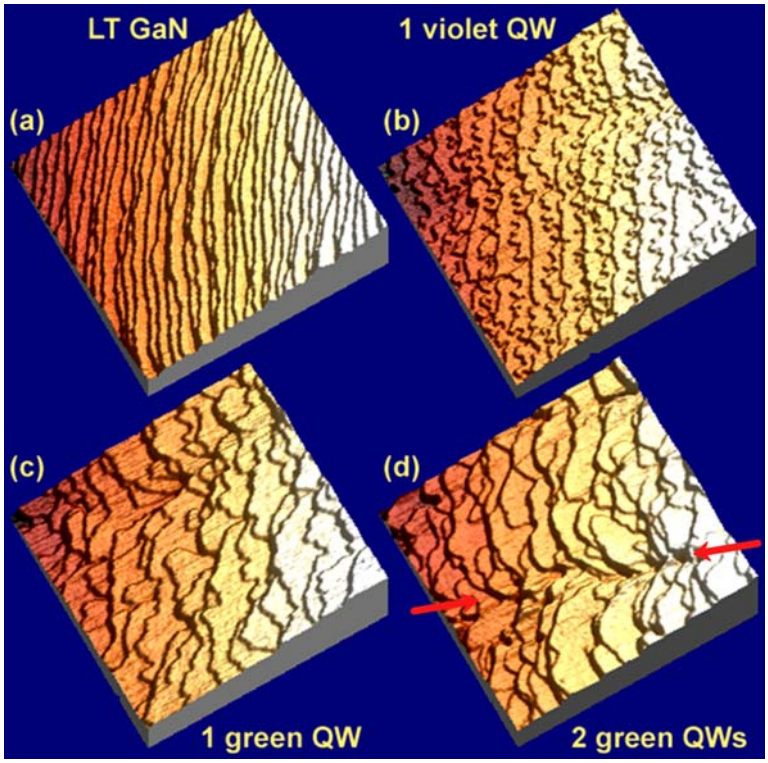

Figure 1. Atomic-force microscopy images measured after the growth of (a) a low-temperature GaN barrier layer, (b) a single $In_{0.10}Ga_{0.90}N$ quantum well (QW) capable of violet light emission, (c) a single $In_{0.20}Ga_{0.80}N$ QW capable of green light emission, and (d) two $In_{0.20}Ga_{0.80}N$ QWs. The image sizes are all 1x1 μm^2. The red arrows mark a valley feature formed at surface of the InGaN MQWs.

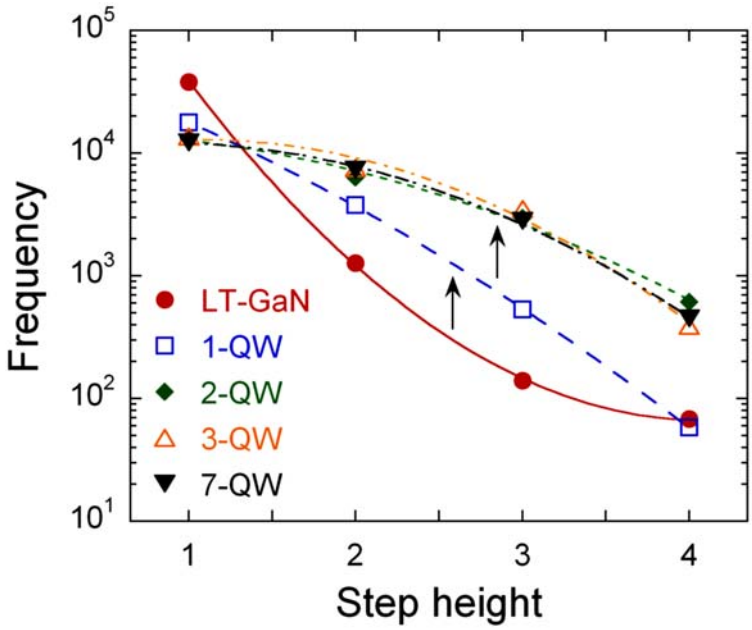

Figure 2. Step-height frequency distributions for a series of $In_{0.20}Ga_{0.80}N$/GaN heterostructures containing varying numbers of quantum wells. The step height is given in units of c/2 where c is the wurtzite lattice parameter along [0001].