Growth Mechanisms that Control InGaN Step Morphology

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Motivation—Despite the high density of dislocations in GaN epitaxial layers grown on sapphire, InGaN-based light-emitting diodes (LEDs) grown on these GaN layers are surprisingly bright and efficient. Several theories have been proposed to explain this light emission efficiency. While important details of these theories vary, a unifying theme is the existence of carrier localization or potential barriers that prevent non-radiative recombination at dislocations or other defects. In this work, we explore nitride surface morphology and step height fluctuations and their role in carrier localization.

Accomplishment—For this study, green wavelength, 5-period InGaN/GaN multiple quantum wells (MQWs) were grown using two different temperatures of 800 and 900 ºC for the GaN barrier layers. The difference in the step morphology is shown in Fig. 1, where the steps heights are given as integer multiples of the c/2 step height of a single III-N monolayer. As evident in Fig. 1, the frequency of double-layer steps is larger for the GaN barriers grown at 800 ºC compared to 900 ºC barriers.

Motivated by this observation, we analyzed the power spectral densities, $g(q)$, of the AFM images shown in Fig. 1. The values of $g(q)$ vs. the reciprocal length scale, q, are calculated from the AFM height-height correlation function. Surface smoothing mechanisms can be discerned from $g(q)$'s power dependence, n, on q [1]. An example plot of this type is shown in Fig. 2, where $g(q)$ is plotted vs. q for the MQW samples shown in Fig. 1. For the MQW sample with 800 ºC barriers, the $g(q)$ vs. q plot gives an exponent, n, of 4.24, while for the MQW sample with 900 ºC barriers, the $\boldsymbol{g(q)}$ vs. $\boldsymbol{q}$ plot gives n = 1.97. Herring showed that n values near 2 are consistent with a smoothing mechanism involving *evaporation and recondensation* of atoms on the surface, while values near 4 are consistent with a smoothing mechanism involving *surface diffusion* [1]. Also shown in Fig. 2 for comparison is the $g(q)$ vs. q fit for the underlying high-temperature-grown GaN templates used for this study, where again $n \sim 2.0$. For other InGaN samples grown under a variety of conditions and composition ranges we typically measure $n \sim 4$.

Thus, our collective work suggests that during MQW growth, barrier growth at or above 900 ºC is smoothed via *evaporation and recondensation* mechanism ($n \sim 2$), which has longer gas-phase diffusion-length scales on the order of 1 to 10 microns. On the other hand, below 900 ºC, smoothing occurs by a surface diffusion ($n \sim 4$) mechanism, which operates over shorter length scales of order 10 to 100 nm. Corroboration for the length scale for the $n = 4$ mechanism is observed in Fig. 2 where the turnover in $g(q)$ for 800 ºC GaN barriers occurs near $q = 10\ \mu m^{-1}$, which corresponds to a length of 100 nm.

Finally, photoluminescence (PL) measurements find brighter luminescence from MQWs with barriers grown at 800 ºC compared to MQWs with barriers grown at 900 ºC, as seen in Fig. 3. X-ray diffraction studies of these two samples find similar indium concentrations (~20%) and QW thicknesses for both MQWs, suggesting that the difference in emission intensity may be due to enhanced localization in QWs grown on the more textured 800 ºC barrier layers.

Significance—Our work provides evidence that changes in growth mechanisms can be used to control InGaN/GaN MQW morphology; more-over, the morphology may be linked to emission efficiency. However, the causal link between the MQW growth morphology and PL emission intensity awaits further study.

[1]. Herring, J. Appl. Phys. 21, 301 (1950).

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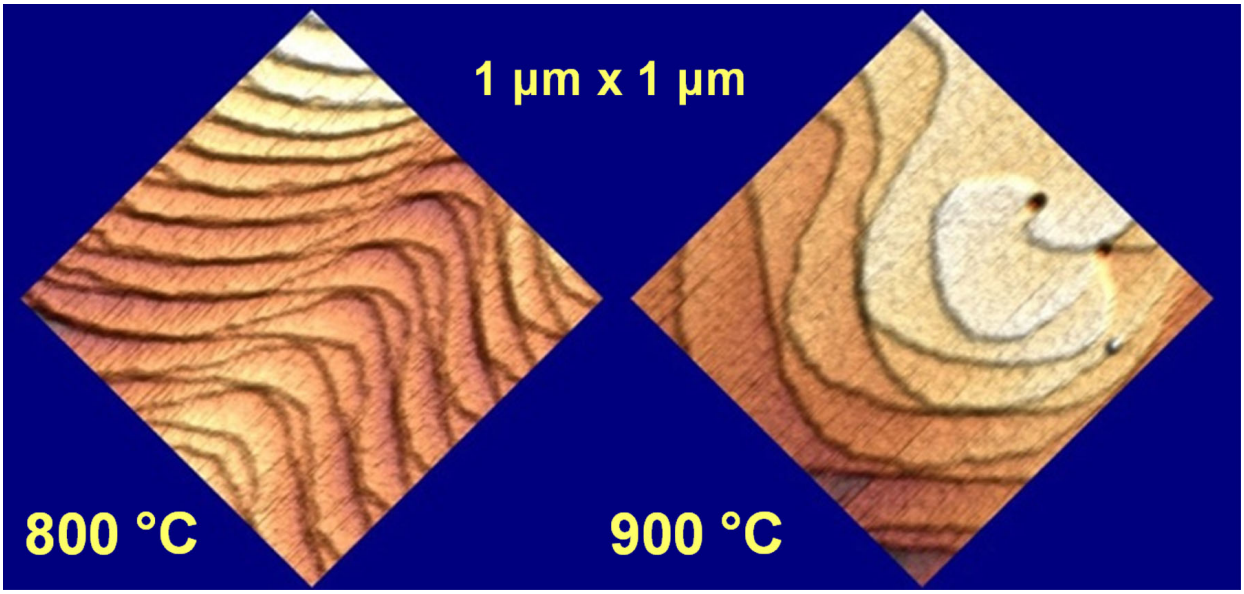

Figure 1. AFM images of green InGaN/GaN multiple quantum wells, with the GaN barriers grown at either 800 or 900 ºC.

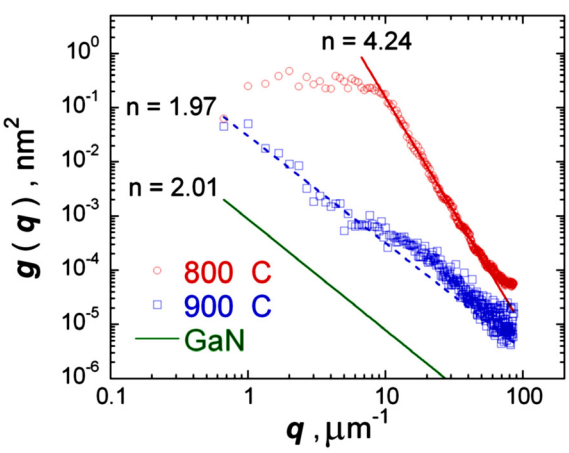

Figure 2. Calculated power spectral density, $g(q)$, plotted as a function of the reciprocal length, q, for green wavelength MQWs with the GaN barrier grown at either 800 °C (red) or 900 °C (blue). The separately measured $g(q)$ for high-temperature grown GaN is also shown in green.

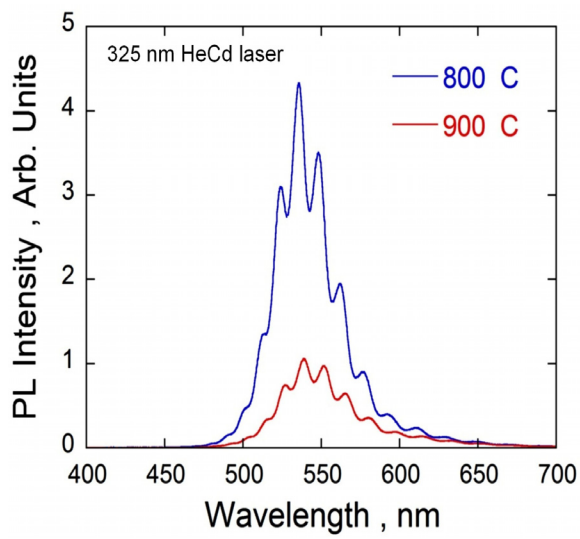

Figure 3. PL intensity for the two MQWs shown in Figure 1 with GaN barrier temperatures of 800 and 900 ºC.