

Nanoscale correlative study between structural defects and local emission properties of red InGaN hybrid single-quantum-wells

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[Background] InGaN serves as an active-layer material of light-emitting diodes (LEDs) spanning the entire visible spectrum, achieved by modulating the indium (In) composition. However, the external quantum efficiency (EQE) is, at most, 10% for InGaN-based red LEDs. [1] The significant reduction in the EQE primarily originates from the degradation of InGaN crystal quality. Iida *et al.* conducted atomic force microscopy (AFM) and cross-sectional scanning transmission electron microscopy measurements on hybrid InGaN red double-quantum-well LEDs, revealing the presence of threading-dislocation (TD)-related V-pits and trench defects. [2] However, the roles of the defects remain controversial.

[Experiment] To elucidate the roles of TDs and trench defects, we conducted AFM and scanning near-field optical microscope-photoluminescence spectroscopy (SNOM-PL) measurements on a hybrid InGaN red single quantum well (SQW), consisting of a blue and a red SQW and without p-type layers. The collection mode SNOM system was developed using cantilever with an aperture diameter of 150 nm. A continuous-wave laser diode with an emission wavelength of 405 nm was employed as the excitation source, with the excitation power set to 8 mW on the sample surface. All experiments were conducted at room temperature.

[Result] Figure 1 presents the AFM image, revealing the presence of TD-related V-pits and trench defects. The trench defects are categorized into three types on the basis of their height relative to a flat QW: lowered-, level-, and raised-center trench defects. A SNOM-PL integrated intensity mapping image taken at the same area is shown in Fig. 2. The SNOM-PL image demonstrates that TDs and all types of trench defects exhibit low emission intensity, indicating that they act as nonradiative recombination centers. The PL spectra acquired from the flat QW and the lowered-, level-, and raised-center trench defects are shown in Fig. 3. Not only blue (~470 nm) and red (~610 nm) but also parasitic green (~540 nm) emissions are observed, indicating the presence of In segregation. The bright emission spots within some trench defects, as observed in the SNOM-PL image, are attributed to the low-indium (In)-content regions caused by In segregation. Unlike previous studies on low In content samples, [3] all the trench defects in our high-In-content sample exhibit a low emission intensity because of the In segregation. Given the correlation of dark emission positions between the blue and red emissions, [4] as well as the reduced screw-type TD density at the surface than that at the n-GaN layer, screw-type TDs must be one of the triggers in the formation of trench defects. Therefore, to enhance the EQE of hybrid InGaN red LEDs, it is crucial to suppress In segregation within trench defects and decrease screw-type TD density.

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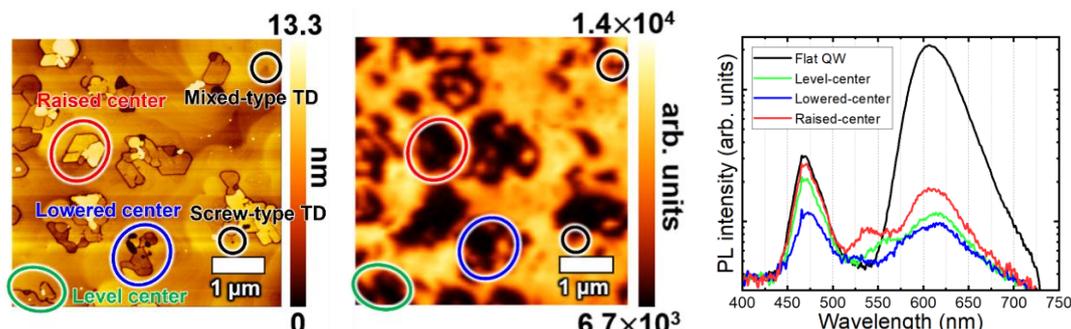


Figure 1. AFM image.

Figure 2. Integrated PL intensity map of red emission.

Figure 3. PL spectra at the flat QW, lowered-, level-, and raised-center trench defects.