doi:10.1017/S1431927610059854
Microsc. Microanal. 16 (Suppl 2), 2010

Looking Inside the Fascinating Nanoworld Controlling Light Emission from InGaN/GaN Quantum Well Devices

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For the last fifteen years scientists have been puzzled over why blue, green and white GaN-based quantum-well LEDs are so bright even though the dislocation density is very high, typically 10^9 cm^{-2} [1]. Initially it was believed that this was because the InGaN quantum well underwent spinodal decomposition into nanometer-size indium rich clusters during growth by MOCVD or MBE [2]. These clusters were believed to localise the carriers, thus preventing their diffusion to dislocations which would quench the light emission since they are non-radiative recombination centres. Such clusters were observed by electron microcopy [3]. However, it was shown that electron-beam damage can rapidly produce In-rich clusters in InGaN, and that such clusters are not visible in low-dose electron microscopy [4, 5, 6], although this has been disputed [7]. In addition, Atom Probe Tomography (APT) has not revealed any In-rich clusters and the In distribution in the quantum wells is consistent with InGaN being a random alloy [8]. Karpov [9] has shown that in a strained InGaN quantum well, the strain suppresses the spinodal decomposition, so no indium-rich clusters are expected thermodynamically for blue and green InGaN LEDs, in agreement with our experiments.

However, if In-rich clusters do not exist in blue and green InGaN quantum wells, what mechanism(s) is localizing the carriers? We have identified three different mechanisms, on length scales ranging from one nm to one hundred nm. First, our quantum mechanical modeling shows that random statistical fluctuations in the InGaN alloy localise the holes on a 1-2 nm length scale. Second, both high resolution electron microscopy [10] and APT [11] reveal that monolayer-height interface steps, typically about 5 nm across, exist at the upper InGaN/GaN quantum well interface. Our modeling shows that these interface steps localise the electrons on a 5-10 nm length scale. Third, we have observed gross thickness fluctuations in the InGaN quantum well width, on a lateral length scale of typically 50-100 nm, in some bright commercial LEDs as well as in some of those we have grown [12]. The majority of dislocations were observed to pass through the gaps in the wells, thus localizing the carriers away from the dislocations on a 50-100 nm length scale. All three mechanisms are strong enough to localise the carriers at room temperature. TEM and APT are therefore absolutely key techniques for solving the long-standing problem of why InGaN/GaN LEDs are so bright when the dislocation density is so high.

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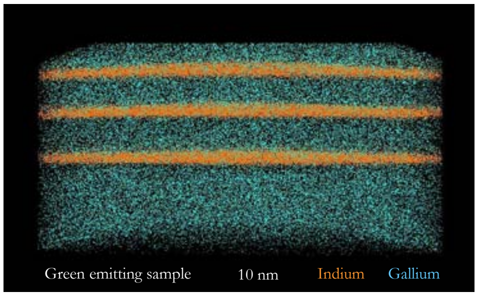

FIG. 1. Atom Probe Tomography image of three green-emitting InGaN quantum wells with GaN barriers. Each dot is one atom. Indium atoms are orange, gallium atoms are blue. Not all gallium atoms displayed (or else individual Ga atoms would be too dense to be visible).

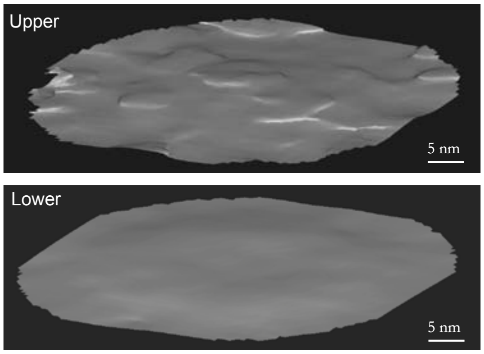

FIG. 2. Isosurfaces (surfaces on which the In concentration is constant) of InGaN/GaN quantum well interfaces from APT data. Top image is the upper interface and bottom image is the lower interface. Average r.m.s. roughness of upper interface: 0.34 nm and lower interface: 0.18 nm. Monolayer-high interface steps clearly visible on upper interface.

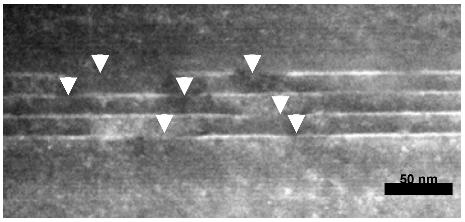

FIG. 3. TEM image of InGaN quantum wells with gross thickness fluctuations.