doi:10.1017/S143192761100780X
Microsc. Microanal. 17 (Suppl 2), 2011

Indium Composition Variation in Nominally Uniform InGaN Layers Discovered by Aberration-Corrected Z-contrast STEM

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The drive for high power, short wavelength, and high temperature optoelectronic devices has contributed to the development of III – V nitride semiconductor materials. The $In_xGa_{1-x}N$ active region based blue to ultraviolet light emitting diode (LED) is one of the most studied systems from this group due to its extraordinarily high efficiency, reaching above 80% internal quantum efficiency [1]. Some studies report lateral composition fluctuations in the InGaN active layers that may act like quantum dots and localize carriers, therefore causing the extraordinary optical properties [2]. Multiple studies used transmission electron microscopy (TEM) to confirm lateral composition fluctuations [3], but later studies reveal these compositional fluctuations can be induced during TEM radiation damage [4].

We have studied InGaN LED structures with Z-contrast imaging and EDS in an aberration-corrected FEI Titan STEM. We find no evidence of lateral composition fluctuations inside the layers, but we found unexpected In-rich bands within regions of nominally uniform In composition. Z-contrast STEM images were acquired with a 24.5 mrad probe semiangle, 24.5 pA probe current, and STEM resolution of 0.8 Å. EDS drift corrected spectrum images were acquired using a 24.5 mrad probe semiangle, ~800 pA probe current, and STEM resolution of ~3 Å. The InGaN/GaN quantum well structure was grown on a (0001) sapphire substrate in a vertical low pressure metal-organic chemical vapor deposition system with nominal layer thicknesses given in the band structure schematic in Figure 1a. TEM [11-20] cross section samples were created by mechanical wedge polishing followed by ion milling in a Fischione 1010 low angle ion mill and a Fischione low energy Nanomill.

Figure 1b shows a Z-contrast STEM image of the InGaN quantum well structure with the growth direction pointing up in the image and the bright contrast coming from the local In concentration. Near the top of the InGaN quantum well structure, the In concentrations follow the nominal structure. The bottom 60 nm was intended to be uniform 1% In, but instead this region shows 4 bright bands of enhanced In separated by about 11 nm. The electron dose required for an image like Figure 1b is <100 C/cm^2, well below the reported beam damage dose of 1050 C/cm^2 [4].

Figure 2 shows the In, Ga, N, and Z-contrast images from an EDS spectrum image of a similar area. The composition maps show larger In concentrations in the top layers, 4 vertical In composition bands inside the 60 nm 1% In layer, Ga deficits where In is concentrated, and evenly distributed N concentration as expected. Figure 3 shows the horizontally integrated In-L/Ga-L ratio profile and the horizontally integrated STEM image profile of the same area, confirming that the STEM image contrast is measuring the In composition. Mechanisms for the formation of these In bands will be discussed [5].

References

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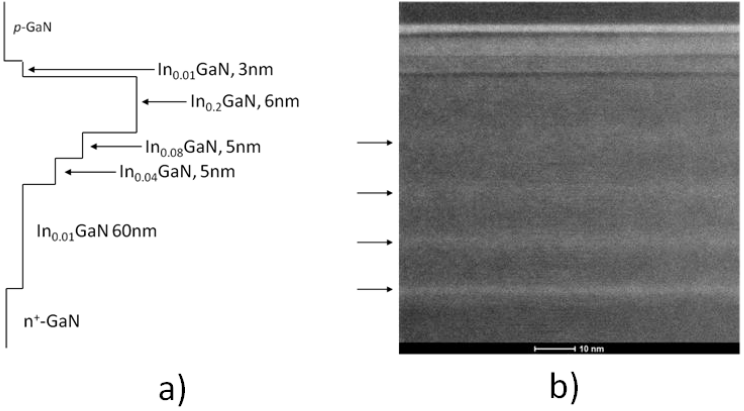

FIG. 1. a) The band structure schematic of the InGaN/GaN quantum well structure. b) Z-contrast image showing vertical composition fluctuations (marked by arrows) within the 60 nm 1% In layer.

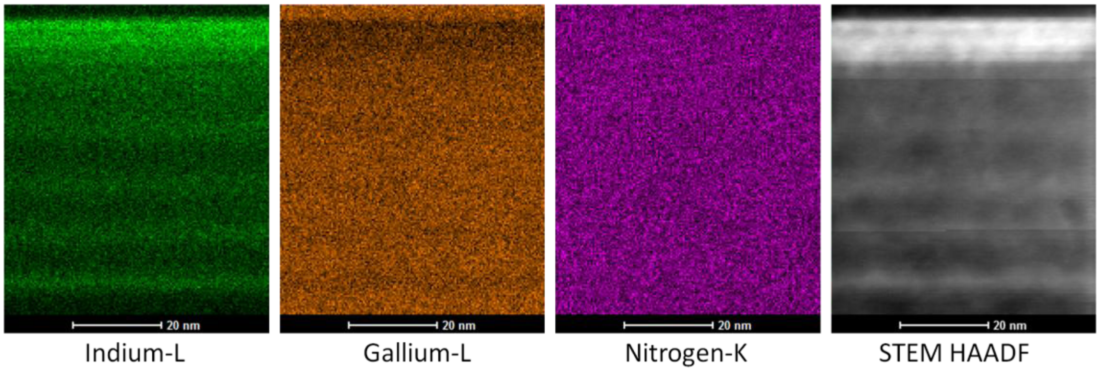

FIG. 2. TIA EDS elemental maps for the In L edge, Ga L edge, N K edge, and the simultaneous HAADF STEM image.

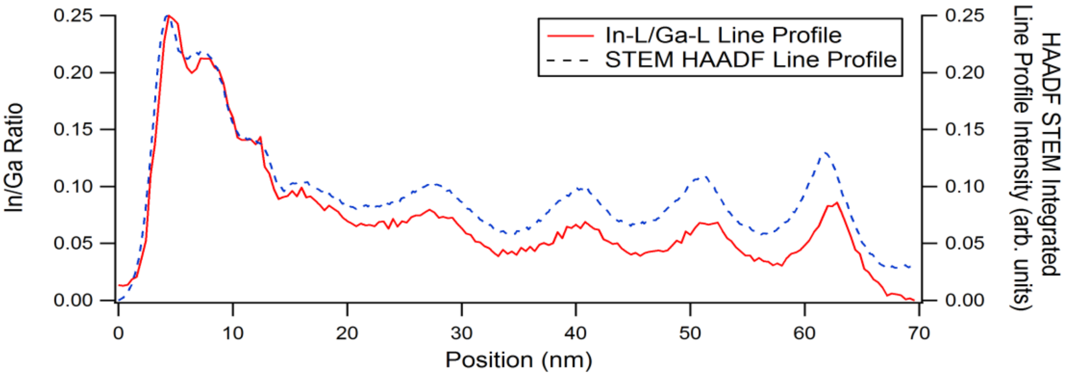

FIG. 3. Integrated line profiles of the indium L edge/gallium L edge ratio and HAADF STEM image of the same area. Growth direction points left in this plot.