Application of high-resolution dark-field electron holography for a study of deep-green light-emitting diodes

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The wall-plug efficiency (WPE) of commercial (In,Ga)N-based light-emitting diodes (LEDs) operating in the blue-violet spectral range exceeds 70%; however above 450 nm the WPE starts to decrease monotonically towards longer wavelength. Since incorporation of indium is limited by a low thermal stability of the InN bond, the epitaxial growth of In-rich quantum wells (QWs) is generally performed at relatively low temperature. Whereas a deterioration of crystalline quality and enhanced impurity incorporation caused by low growth temperature are frequently cited among possible reasons of the luminous efficacy drop.

We explore an alternative way to enhance In incorporation, which consists in a predisposition of certain amount of In prior to the (In,Ga)N QW growth. In this approach a delayed In incorporation together with a surface segregation effect may produce a strong composition gradient in the growth direction. In order to examine experimentally this effect we use a recently developed dark-field electron holography (DFEH). The composition determination is done in a similar manner as by the high-resolution transmission electron microscopy (HRTEM), but as compared to HRTEM the DFEH has a superior precision, which can be better than 1% in the case of (In,Ga)N.

The capacities of DFEH are illustrated by studying a series of a single QW deep-green LEDs grown by metal-organic vapor phase epitaxy. We show that owning to the InN predisposition an In concentrations up to 30% can be obtained at a growth temperature above 800 °C. All the (In,Ga)N QWs have an abrupt lower interface and a regular two-dimensional morphology. The surface segregation effect results in a smoothing of the upper QW interface and a penetration of about 1-4% of InN into the GaN barrier (Fig. 1). The amount InN penetrated into the GaN barrier and the resulting shape of the composition profile strongly depend on the growth conditions, such as a QW growth time or temperature. In particular QWs with almost no composition gradient can be obtained (blue curve at Fig. 1).

The experimentally measured composition profiles were used to calculate the electroluminescent (EL) properties of the studied LEDs. The simulated properties are compared with those measured experimentally from the real structures, which exhibit electroluminescence in the range 507 – 585 nm and the factors governing the luminous efficacy behavior of deep-green LEDs are discussed.

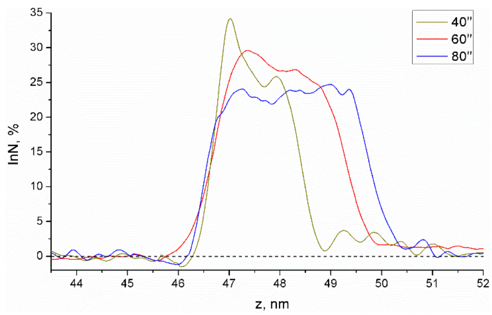

Fig. 1 Composition profiles obtained with DFEH from the structures with a different QW growth time. The dash line shows a level of zero concentration.