TEM/STEM characterization of polar and semipolar InGaN quantum dots

A. Lotsari¹, T. Koukoula¹, Th. Kehagias¹, G.P. Dimitrakopulos¹*, I. Häusler², A. Das³, E. Monroy³, Th. Karakostas¹, and Ph. Komninou¹

1. Department of Physics, Aristotle University of Thessaloniki, GR 541 24 Thessaloniki, Greece
2. Institut für Physik, Humboldt-Universität zu Berlin, AG Kristallographie, Newtonstrasse 15, D-12489 Berlin, Germany
3. CEA-CNRS Group “NanoPhysique et SemiConducteurs,” INAC/SP2M/NPSC, CEA-Grenoble, 17 rue des Martyrs, 38054 Grenoble, Cedex 9, France

*gdim@auth.gr

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Group III-nitride semiconductors and their alloys have attracted attention as prominent materials for high efficiency optoelectronic devices. Especially, the ternary InGaN alloy, due to its adjustable direct band gap, is acknowledged as a highly appealing material that covers a wide wavelength range. Semipolar growth orientations are employed in order to partially eliminate the internal polarization present in polar growth that leads to carrier separation and reduces the internal quantum efficiency (IQE). Further enhancement of the IQE can be attained with the utilization of quantum dot (QD) nanostructures that act as active recombination centres.

We present a structural analysis of polar (0001) and semipolar (1122) self-assembled InGaN/GaN QD superlattices grown by plasma-assisted molecular beam epitaxy (PA-MBE) using transmission and scanning transmission electron microscopy (TEM/STEM) techniques [1]. The superlattices consisted of 10 InₓGa₁₋ₓN QD periods separated by 5 nm GaN barriers and were deposited on MOVPE GaN-on-sapphire templates. Two sets of growth temperatures were studied, i.e. high (650-510°C) where indium desorption is active, and low (460-440°C) where indium desorption is negligible.

Regarding polar QDs, the sample grown at a high-T of 600°C with nominal thickness of 5 monolayers (ML) showed optimum morphological characteristics. Figure 1(a) is a z-contrast STEM image of the super lattice, along the [1120] zone axis, showing surface and embedded QDs. The surface QDs exhibited truncated pyramidal morphology with {1013} and {1014} side facets. Figure 1(b) is a z-contrast image showing that the embedded QDs exhibited similar facets. The GaN/InGaN bottom interfaces of the QDs were found to be structurally sharper compared to the upper QD interfaces. This is attributed to indium out-diffusion from the QDs when they are overgrown by the GaN barriers due to the difference in growth temperature between InN and GaN. For both surface and embedded QDs the average height was ~2 nm and their base width varied from ~10 nm to ~24 nm. No misfit dislocations were observed at the GaN/InGaN interface, suggesting an elastically strained heterostructure. Hence in the strained two-dimensional InGaN layers, QD formation was the only relaxation mechanism. At low-T, the growth conditions did not favour QD formation, and the structure was heavily distorted by multiple basal stacking faults (BSFs). The overlapping of BSFs resulted to local structural transformations from wurtzite to sphalerite. Thus, clearly resolved QDs at low-T could not be identified. Hence optimized growth conditions could be established in order to grow QDs as well as reduce indium interdiffusion.

Contrary to polar, semipolar QDs were successfully grown regardless of growth temperature, although the different temperature affects the QD morphology. As shown in Figure 2(a) when a low-T was employed, the QD layers exhibited a corrugated morphology, while in high-T, InGaN QDs attained a more lenticular morphology with average height equal to ~2 nm and width ~15 nm [Figure 2(b)]. The main characteristic of heteroepitaxial semipolar samples is the large threading dislocation (TD) and BSF density. TDs originated from the MOVPE GaN template and propagated through the superlattice. These TDs lied on the (0002) basal planes but were often found to change their
orientation when they intersected with the InGaN layers, as illustrated by arrows in Figure 2(a). This TD bending was attributed to the influence of the elastic strain in the QD superlattice. The elastic strain state of the layers was also found to promote TD half-loops [2]. As a result of the TD-induced distortion, the InGaN wetting layers changed their orientation at the vicinity of TDs by about 15°-26° relative to the (1122) plane. Preferential nucleation of QDs on these depressions was observed. Figure 2 (c) illustrates one of these inclined QDs which were generally larger in size and more faceted. Geometrical phase analysis was applied for the measurement of the elastic strain in the QD layers, and these measurements were correlated to the indium content.

References

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Figure 1. (a) Z-contrast STEM image of the high-T polar sample along the [1120] zone axis. Some of the surface and embedded QDs are indicated. (b) Detail of (a) showing QD side facets consistent with the \{10\13\} and \{10\14\} planes. (c) HRTEM image of a surface InGaN QD showing the wurtzite hexagonal stacking.

Figure 2. (a) HRTEM image along [1\100], showing the low-T semipolar sample where QD layers have a corrugated morphology. The arrows denote TDs that appear to bend upwards upon interaction with the superlattice. (b) HRTEM image showing an overview of the high-T semipolar superlattice. The TDs that cross the heterostructure (arrowed) cause the InGaN wetting layers to change their orientation from the (1122) plane, and QDs nucleate also on these inclined planes. (c) Detail of an inclined QD with a faceted morphology (facets indicated by dashed lines).