Influence of AlN/(Al,Ga)N superlattices on the defect densities in UV-LEDs formed on high-temperature AlN layers on sapphire

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In recent years AlGaN alloys have been intensively investigated for the application in deep ultraviolet (UV) light emitting diodes and laser diodes. Fabrication of high-efficiency AlGaN-based devices operating in the UV-range requires UV-transparent smooth thick AlN buffer layers. A large lattice mismatch between sapphire and AlN results in generation of a large number of threading dislocations. A way to reduce the threading dislocation density is to grow strained short period (Al,Ga)N/AlN superlattices (SL) on AlN acting as dislocation stopping barriers. Growth of such structures is a challenging task, since the lattice misfit between sapphire substrates and AlN buffers as well as between AlN and (Al,Ga)N often leads to strain relaxation through surface roughening and/or crack formation. These undesirable effects strongly limit the device performance. Thus, fabrication of smooth, crack free (Al,Ga)N layers on sapphire with a low defect density is a challenging task.

This study reports on structural characterisation of AlN buffer layers as well as subsequently grown (Al,Ga)N/AlN SLs using STEM HAADF imaging, EDXS, CBED and conventional TEM diffraction contrast imaging. The investigated structures were grown on sapphire by metalorganic vapour phase epitaxy (MOVPE). About 1 µm thick AlN buffer layers were grown at high-temperature (approx. 1400°C) with different NH_3/TMAl preflow conditions before nucleation layer deposition. TEM diffraction contrast analysis shows that simultaneous NH_3/TMAl switching on leads to both smooth surface morphology and a decreased screw dislocations density: from $5x10^9$ for TMAl preflow to $8x10^8$ cm^{-2} for simultaneous NH_3/TMAl switching on (Fig. 1). The edge dislocation density remains about the same ($\sim 2x10^{10}$) [1]. Furthermore, a precise control of NH_3/TMAl preflow conditions is a crucial factor which tunes the layer polarity.

Different combinations of short period superlattices consisting of 30 times AlGaN/AlN layers on AlN template, 30 times AlGaN/AlN layers on AlGaN template and 80 times GaN/AlN layers were grown for a strain reduction between AlN and further deposited AlGaN. The GaN/AlN supperlattice introduces the largest shear strain into the system due to the highest lattice mismatch between the AlN and GaN layers. TEM analysis shows that this causes some dislocations to bend and annihilate inside the superlattice (Fig. 2). Furthermore, a large number of dislocations form loops in the AlGaN top layer. EDXS analysis shows intermixing of the superlattice layers with the AlN buffer underneath and the AlGaN overlayer indicating the thermal instability of AlGaN during the first deposition stages (Fig. 3).

High-resolution STEM HAADF imaging allows a precise measurement of layer thicknesses. It has been applied to evaluate the thickness of the GaN/AlN SL layers as well as InAlGaN MQWs forming an active region (Fig. 1 and 4).

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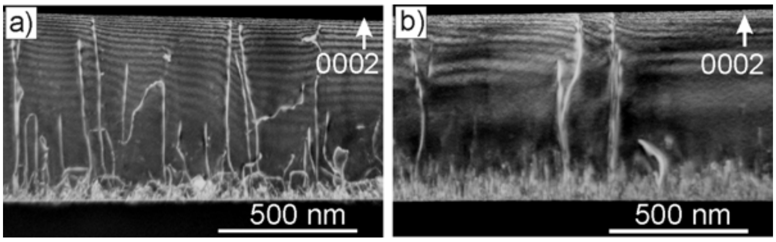

Figure 1. Weak-beam images showing screw and mixed dislocations in the samples (a) with TMAl pre-flow (40 s) and (b) with simultaneous NH_3/TMAl switching.

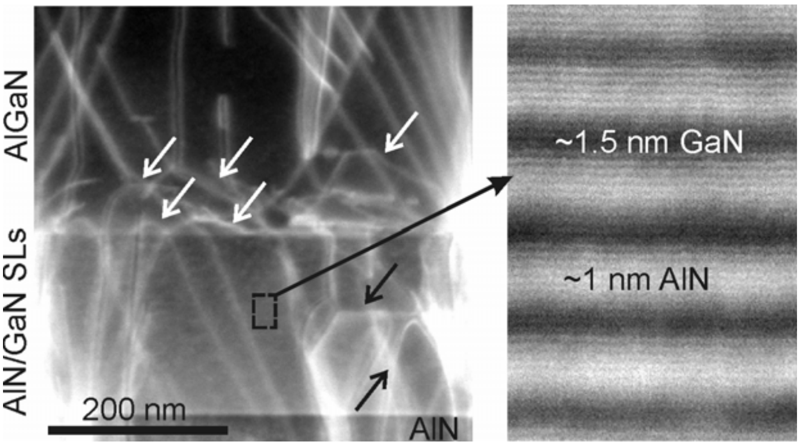

Figure 2. STEM dark-field image showing strong dislocation contrast. Some dislocation lines bend and annihilate inside the AlN/GaN SL and above it in AlGaN (see black and white arrows). An inset shows a HAADF image of AlN/GaN layers with a thickness of about 1 nm for AlN and about 1.5 nm for GaN.

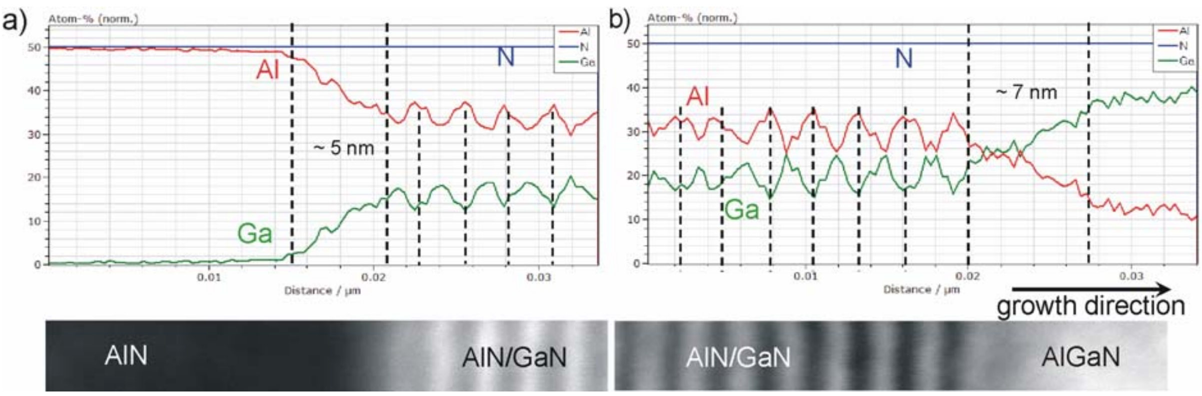

Figure 3. EDXS line scan measurements carried out with a spot size of 0.7 nm showing a transition a) from AlN buffer to AlN/GaN SL and b) from SL to the AlGaN top-layer.

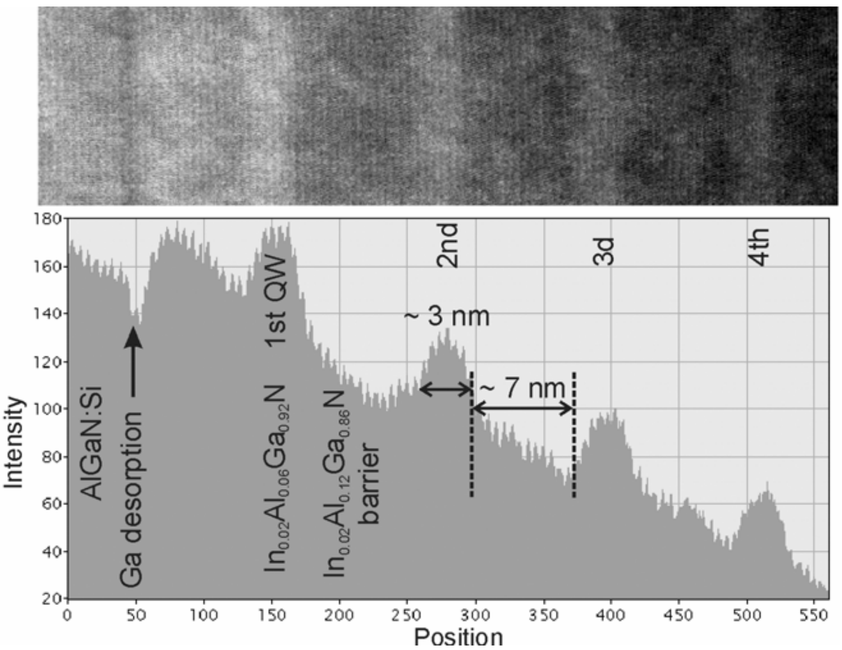

Figure 4. HAADF image of smooth homogeneous InAlGaN MQWs and a grey scale scan along the growth direction used for the thickness evaluation. Despite the low difference between mean atomic numbers of the layers ($\Delta Z \sim 0.3$) the change in the image intensity is clearly visible. The estimated InAlGaN QW thickness amounts to about 3 nm.

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