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Analysis of crystal orientation in AlN layers grown on m-plane sapphire

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Most of today's III-nitride based device heterostructures are grown along the c-axis direction of the wurtzite structure (so called c-plane layers). However, optoelectronic devices obtained on the basis of c-plane nitrides suffer from spontaneous and piezoelectric polarisation fields which appear in the noncentrosymmetric wurtzite structure along the polar c-axis. Thus, growth of so-called non-polar (i.e. m-plane (10-10) or a-plane (11-20)) as well as semipolar (i.e. (11-22), (10-13), etc.) nitride layers has been intensively investigated in the last decade [1]. Whereas most of the recent studies focus on the growth of nonpolar and semipolar GaN layers, less attention has been given to AlN. The AlN-based heterostructures are especially important for light emitters operating in deep ultra-violet (UV) spectral range (below 280 nm), which e.g. can be used for water purification, gas sensing and medical diagnostics.

Our study reports on the structure of AlN layers grown on m-plane (1-100) sapphire by metal organic vapour phase epitaxy. Using high-resolution transmission electron microscopy (HRTEM) and scanning nanobeam diffraction (SNBD) [2] we will show that variation of V/III ratio during the nitride deposition allows tuning of the layer orientation: from a preferentially oriented semipolar (11-22) AlN layer at a V/III ratio of 1050 to a layer consisting of differently oriented crystallites at a V/III ratio of 630.

Figure 1 shows three major orientations observed in the AlN layers on m-plane sapphire: semipolar {11-22}AlN and {10-13}AlN as well as non-polar m-plane {1-100}AlN. These orientations are present simultaneously in AlN layers grown at the V/III ratio of 630 (Fig. 2a) in accordance with XRD results. Basal plane stacking faults (BSF) are frequently observed in these crystallites with a different inclination angle depending on the crystallite orientation. The different crystallite orientation is visible in Fig. 2b showing exemplary crystallographic orientation maps obtained by SNBD. In the obtained images the (11-22)AlN layer appears at the interface to the sapphire substrate, whereas differently oriented crystallites are visible above this layer. We attribute the presence of a semipolar (11-22)AlN layer at the substrate interface to the projection effect in the TEM specimen and not to an initial formation of a uniformly (11-22)-oriented interfacial layer. Except for the (11-22)-orientation, all the other orientations present in the sample are governed by a common relationship along one direction, i.e. [11-20]AlN || [0001]Al_2O_3 (see the green coloured area in Fig. 2b), which has been previously observed in GaN layers [3]. This in-plane relation results in a lattice mismatch of about 4%.

An increase of the V/III ratio to 1050 leads to a predominant formation of (11-22)AlN layers with a BSF density of about $2\text{-}4\cdot10^5$ cm^{-1} (Fig. 3a). Atom force microscopy shows that these layers exhibit a complex surface morphology with a periodic undulation along [1-100]AlN and a number of additional dot like structures on the layer surface [4]. The lateral size and height of these dot-like structures strongly depend on the reactor pressure. Cross-sectional TEM analysis reveals that these structures can be attributed to differently oriented crystallites (Fig. 3b,c), which might randomly nucleate on the m-plane sapphire surface, coalesce with (11-22)AlN nuclei during the further growth and protrude from the surface of (11-22)AlN layers due to the different growth rates.

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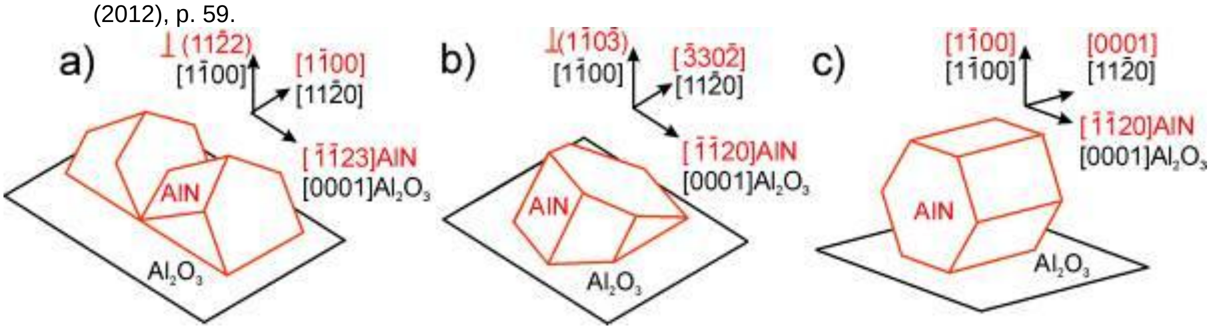

Figure 1. Sketch of different epitaxial orientation relations observed in AlN layers grown on m-plane sapphire: a) semipolar (11-22) orientation; b) semipolar (10-13) orientation; c) non-polar m-plane (1-100) orientation.

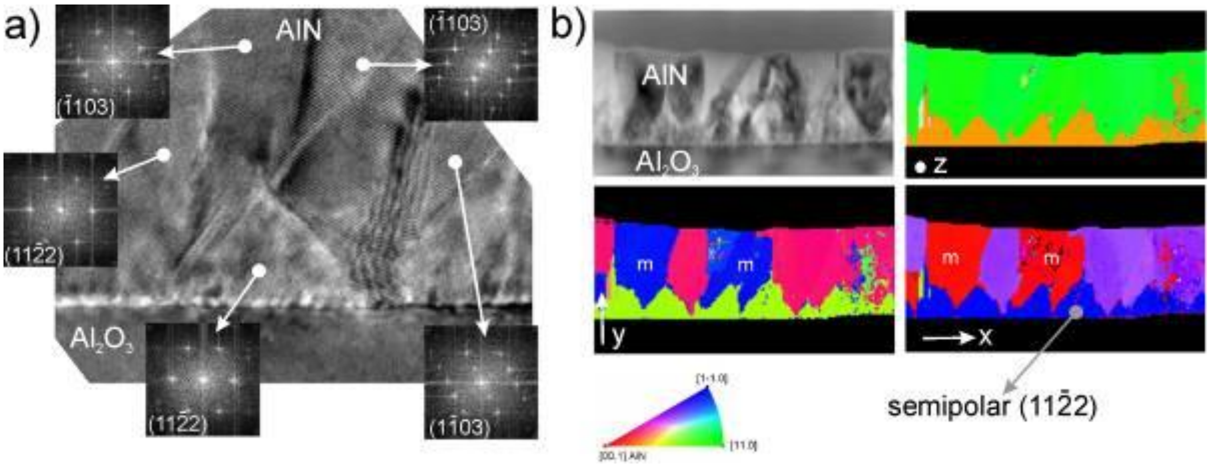

Figure 2. Structure of AlN layers grown on m-plane sapphire at a III/V ratio of 630: a) cross-sectional HRTEM image showing differently oriented crystallites (the different growth planes are indicated in the corresponding Fourier spectra); b) cross-sectional crystallographic orientation maps obtained by SNBD and the corresponding color zone selector (m-plane oriented crystallites are indicated in the maps).

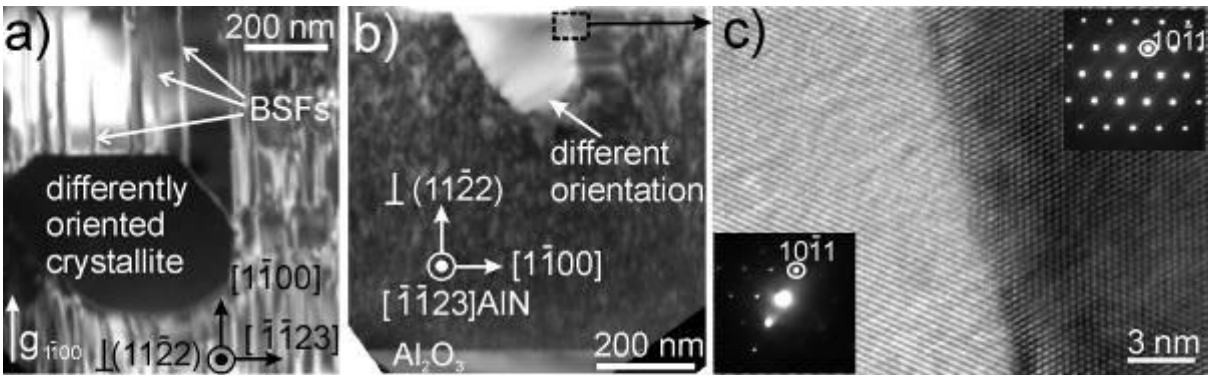

Figure 3. Structure of AlN layers grown on m-plane sapphire at a III/V ratio of 1050: a) plan-view dark-field image of (11-22)-oriented AlN layer containing BSFs and an embedded crystallite of a different orientation; b) cross-sectional bright-field image obtained in zone axis showing semipolar (11-22)AlN with an embedded crystallite of a different orientation; c) HRTEM image of a region marked in (b) with the corresponding diffraction patterns show that the crystallite is rotated in the (10-11) plane with respect to the semipolar (11-22)AlN matrix.