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Epitaxial growth of 6H-AlN on *M*-plane SiC by plasma-assisted molecular beam epitaxy

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Abstract

A new AlN polytype is grown on *M*-plane 6H-SiC by plasma-assisted molecular beam epitaxy. A 6H stacking order is deduced from reflection high-energy electron diffraction patterns and the occurrence of an additional $[1\,1\,\bar{0}\,0]_{6H}$ reflection in X-ray diffraction $\omega - 2\theta$ scans. A predominant 6H stacking, intersected by thin lamellae with 2H stacking, is directly observed in high-resolution transmission electron microscopy. Atomic force microscopy (AFM) shows a stripe-like morphology with a roughness of 1.7 nm and a peak-to-valley distance of 12 nm over 25 m^2. The AlN films are partially relaxed and of good crystal quality as evidenced from X-ray diffraction ω-scans with a line width of 130 arcsec for both symmetric and asymmetric reflections.

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1. Introduction

Group-III nitride epitaxial layers with a non-polar face, such as the {1 1 2 0} (*A*-plane) or {1 1 0 0} (*M*-plane), have attracted interest in recent years due to the absence of the undesirable effects of built-in electric fields resulting from the spontaneous and piezoelectric polarization along the $\langle 0\,0\,0\,1 \rangle$ direction [1–4]. Due to the potentially high electrical and high thermal conductivity of SiC substrates [8], an increasing number of studies has been carried out on nitride growth on non-polar *A*- or *M*-plane SiC substrates [9–12]. A difficulty in the growth of nitrides on non-polar SiC arises from the different stacking order, which is 4H or 6H for SiC, while the stable polytype of all nitrides is the wurtzite structure which exhibits 2H stacking order. Unless a polytype replication occurs, this stacking mismatch should lead to a high density of stacking faults [11] for films grown on the non-polar faces of SiC. However, polytype replication has indeed been observed for growth of AlN on *A*-plane [10] as well as on *M*-plane 4H-SiC [12], while AlN growth on both *A*-plane [9] and *M*-plane 6H-SiC was suggested to result in a 2H stacking order [13].

Here, we perform a detailed study on the growth of AlN on *M*-plane 6H-SiC substrates to determine which stacking order is present and find a coexistence of both 2H and 6H regions, showing that polytype replication is indeed possible under certain conditions.

2. Experimental details

The samples were grown by plasma-assisted molecular beam epitaxy in a VTS-CreaTecTM system (base pressure 1×10^{10} mbar) equipped with a solid-source effusion cell for Al and an AddonTM radio-frequency nitrogen plasma source for producing active N. 6N nitrogen gas was used which was further purified to ppb levels by a getter filter. Epi-ready n-type 6H-SiC(1 1 0 0) substrates, obtained from NOVASiCTM, were first thoroughly outgassed in vacuum at 400 °C for 1 h before transferring them into the growth chamber. Before initiating growth, the substrates were subjected to several cycles of Ga deposition and flash-off at elevated temperatures in order to remove residual sub-oxides from the SiC substrate surface [14]. This procedure

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was also used to calibrate the growth temperature. We deposited 100 nm thick AlN layers under Al-rich conditions with a N flow of 0.3 sccm and a plasma power of 300 W at a growth temperature of about 780 °C. Excess Al was consumed at the end of growth by exposing the surface to the N flux.

3. Results and discussion

Reflection high energy electron diffraction (RHEED) patterns were obtained in the $\langle 11\bar{2}0\rangle$ azimuth before growth from the 6H-SiC substrate, as shown in Fig. 1 (top), and after growth from the AlN layer, as shown in Fig. 1 (bottom), respectively. In contrast to 2H-AlN (indicated by the white arrows in Fig. 1, bottom), the periodicity observed matches that of the substrate. This shows that the AlN layer has virtually the same *c*-lattice constant as 6H-SiC, indicating a 6H stacking.

Atomic force microscopy (AFM) images (see Fig. 2) display the characteristic stripe-like morphology of *M*-plane nitrides with a RMS roughness of about 1.7 nm and a peak-to-valley distance of about 12 nm over an area of 25 μm^2. These values are comparable to state-of-the-art *M*-plane GaN films. Larger AFM scans show that the roughness and the step height increases in areas where Al droplets were formed during growth. The stripe-like features appear to origin in these regions. A reduction of these feature were observed in samples grown with lower Al flux or at higher temperatures.

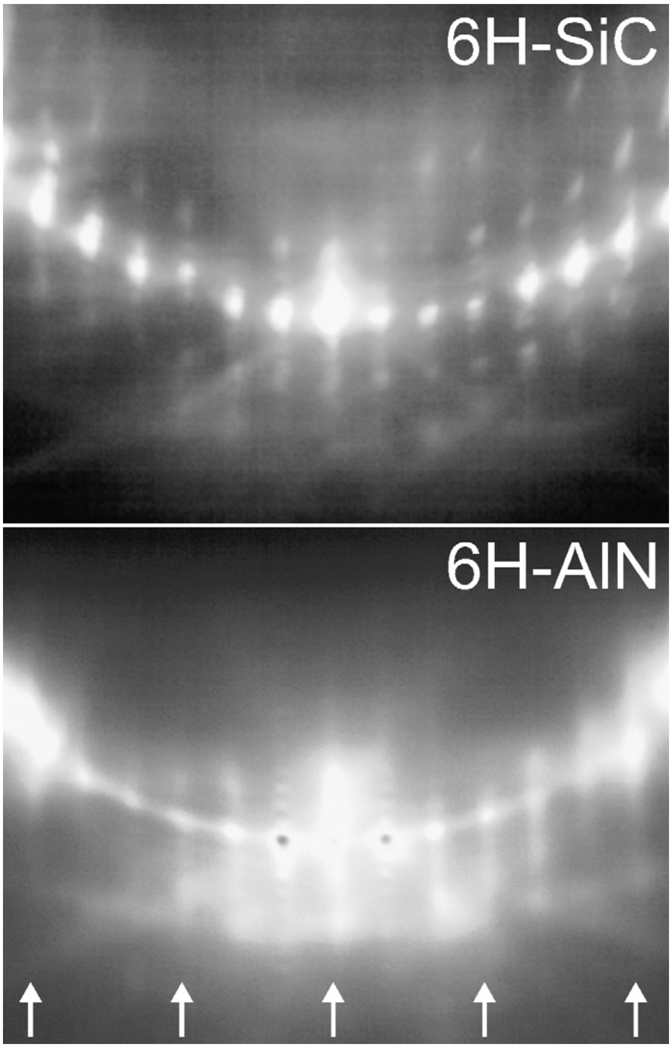

Fig. 1. RHEED patterns of the SiC substrate (top) and after deposition of a ~100 nm thick AlN film (bottom) recorded along the $\langle 11\bar{2}0\rangle$ azimuth.

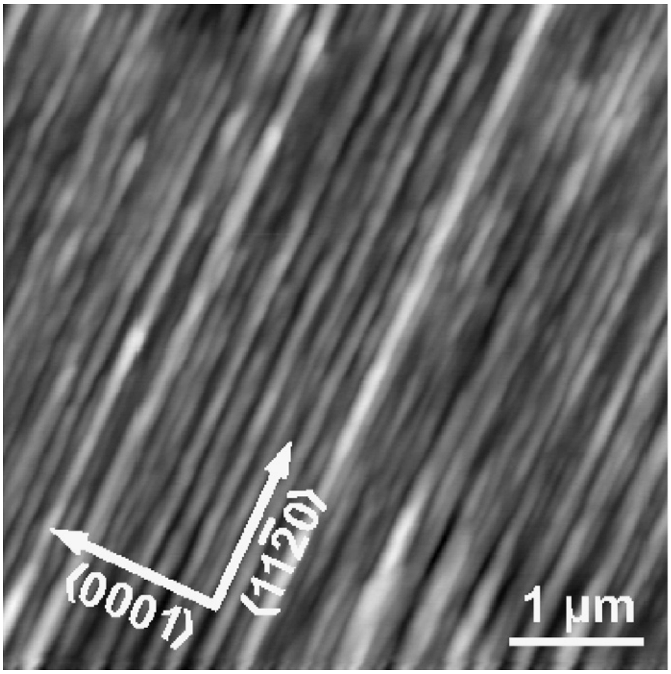

Fig. 2. $5\times 5\,\mu m^2$ AFM image of a 100 nm thick AlN film grown on 6H-SiC. The *z*-range of the image is 15 nm.

To confirm the existence of this new 6H polytype of AlN, we performed skew-geometry $\omega - 2\theta$ X-ray diffraction measurements using a Philips X'Pert ProTM triple-axis X-ray diffractometer with a Si(0 2 2) analyzer crystal. The 6H phase has a three times larger *c*-lattice constant as compared to 2H phase and therefore shows (analogously to RHEED) additional X-ray diffraction reflections. For instance, while the $[1\bar{1}03]_{6H}$ reflection corresponds to the $[1\bar{1}01]_{2H}$ reflection, for the $[1\bar{1}01]_{6H}$ reflection no corresponding reflection exists for the 2H structure. Fig. 3 (top) shows skew-geometry $\omega - 2\theta$ X-ray diffraction scans across the $[1\bar{1}01]$ and $[1\bar{1}03]$ reflections of *M*-plane 6H-SiC. The $[1\bar{1}01]_{6H}$ reflection of AlN is clearly resolved and is of similar intensity as the $[1\bar{1}03]_{6H}/[1\bar{1}01]_{2H}$ reflection to which the entire film contributes, showing that a significant fraction of the film is of the 6H polytype.

Associated ω-scans reveal a FWHM of 0.037° for the symmetric $[1\bar{1}00]$ reflection (not shown), 0.04° for the asymmetric $[1\bar{1}01]$ and 0.063° for the asymmetric $[1\bar{1}03]$ reflections (Fig. 3 bottom). These values are drastically lower than those obtained for *M*-plane 2H-GaN films grown on 6H-SiC, indicating the presence of large, undistorted 6H regions, and a comparatively high crystal

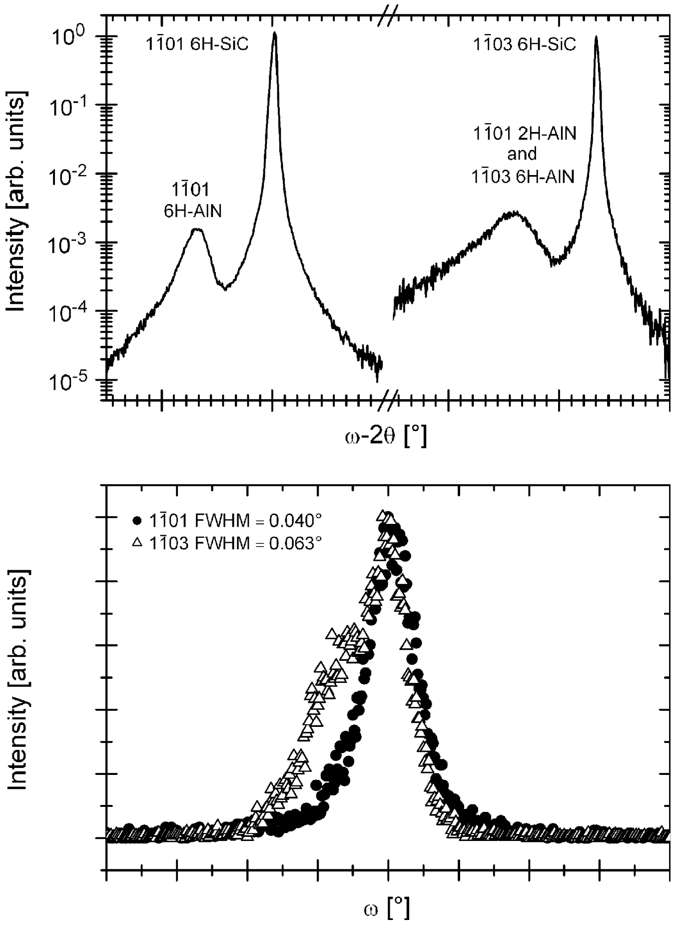

Fig. 3. Skew-geometry $\omega{-}2\theta$ X-ray diffraction scans recorded across the $[1\,\bar{1}\,0\,1]$ and $[1\,\bar{1}\,0\,3]$ reflections of 6H-SiC (top). Associated ω scans across the same reflections (bottom). The second peak in the ω scan arcoss the $[1\,\bar{1}\,0\,3]$ reflection is a result of the imperfect substrate.

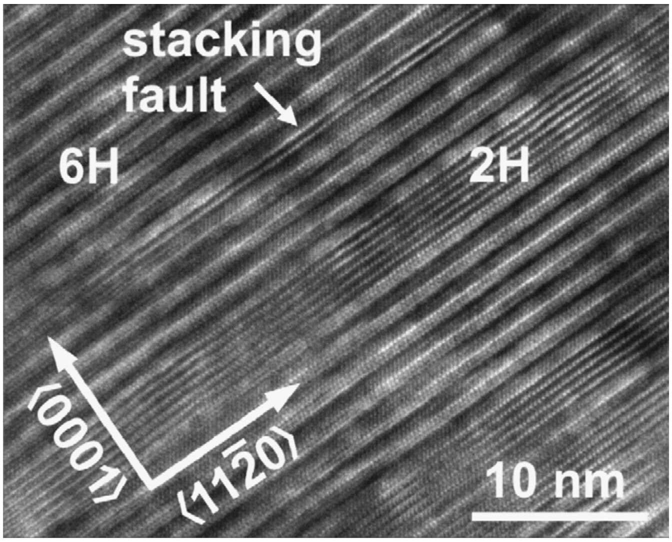

Fig. 4. (1 1 0 0) plan-view HRTEM image of the *M*-plane AlN film.

quality. A further analysis of the X-ray diffraction data shows that the AlN film partially relaxes in the $\langle 0\,0\,0\,1\rangle$ ($\Delta c/c_{\text{SiC}} = -0.477\%$) and the $\langle 1\,1\,\bar{2}\,0\rangle$ ($\Delta a/a_{\text{SiC}} = 0.6\%$) directions. Compared to bulk AlN, the film is orthorhombic with strain components $\varepsilon_{\langle 1\,1\,\bar{2}\,0\rangle} = 0.388\%$, $\varepsilon_{\langle 1\,\bar{1}\,0\,0\rangle} = 0.1\%$ and $\varepsilon_{\langle 0\,0\,0\,1\rangle} = 0.67\%$.

Fig. 4 shows a plan-view high-resolution transmission electron microscopy (HRTEM) image of the AlN films taken in a JEOL3010 microscope operating at 300 kV. A predominant 6H stacking, intersected by thin lamellae with 2H stacking, is clearly visible in the plan view image, thereby confirming the findings of the X-ray analysis.

4. Summary

AlN was grown on *M*-plane 6H-SiC by plasma-assisted molecular beam epitaxy. RHEED patterns of the AlN film show the same periodicity observed for the 6H-SiC substrate, indicating that the AlN layer has virtually the same *c*-lattice constant as compared to 6H-SiC and a 6H stacking order. AFM images show the characteristic stripe-like morphology of *M*-plane nitrides with a RMS roughness of about 1.7 nm and a peak-to-valley distance of about 12 nm over an area of 25 μm^2. These values are comparable to state-of-the-art *M*-plane GaN films. From X-ray diffraction scans, it is deduced that the AlN films are partially relaxed and of good quality as evidenced by ω-scans line widths of around 130 arcsec for both symmetric and asymmetric reflections. The 6H stacking order is confirmed by the occurrence of an additional $[1\,\bar{1}\,0\,1]_{6H}$ reflection-peak in X-ray diffraction skey-geometry $\omega{-}2\theta$ scans and is directly observed in high resolution transmission electron microscopy.

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