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Semipolar GaN grown on m-plane sapphire using MOVPE

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We have investigated the MOVPE growth of semipolar gallium nitride (GaN) films on $(10\bar{1}0)$ m-plane sapphire substrates. Specular GaN films with a RMS roughness (10x10 µm^2) of 15.2 nm were obtained and an arrowhead like structure aligned along $[\bar{2}113]$ is prevailing. The orientation relationship was determined by XRD and yielded $(2\bar{1}\bar{1}2)_{GaN} \parallel (10\bar{1}0)_{sapphire}$ and $[\bar{2}113]_{GaN} \parallel [0001]_{sapphire}$ as well as $[\bar{2}113]_{GaN} \parallel [000\bar{1}]_{sapphire}$. PL spectra exhibited near band edge emission accompanied by a strong basal plane stacking fault emission. In addition lower energy peaks attributed to prismatic plane stacking faults and donor acceptor pair emission appeared in the spectrum. With similar growth conditions also $(10\bar{1}\bar{3})$ GaN films on m-plane sapphire were obtained. In the later case we found that the layer was twinned, crystallites with different c-axis orientation were present.

1 Introduction Radiative recombination lifetimes in InGaN quantum wells (QW) on c-plane GaN are affected by the strong piezoelectric and spontaneous polarization fields. A red shift is observed in c-plane QWs, as well (quantum confined Stark effect, QCSE). The fields can be reduced by growth of GaN on semi- or nonpolar surface planes [1]. It is expected that nonpolar or semipolar GaN will lead to an improvement in efficiency of GaN based optoelectronic devices beyond the physical limits of c-plane GaN [2]. Nonpolar GaN, such as $(2\bar{1}\bar{1}0)$ a-plane or $(10\bar{1}0)$ m-plane, is free of polarization fields [3]. For certain semipolar orientations the polarization field across InGaN/GaN QW systems can be zero as well [1]. Even if these conditions are not met, fields will be reduced compared to c-plane GaN. Semipolar GaN films can be grown on (100) and (110) spinel substrates [4,5], semipolar GaN substrates from c-plane boules as well as m-plane sapphire. LEDs [6, 7] and lasers [8] grown on semipolar GaN substrates were recently demonstrated. It was found that LEDs on semipolar GaN substrates have a much higher output power than on m-plane sapphire [9] due to much lower defect density. However, semipolar bulk GaN substrates so far are very limited in size and also much more expensive than m-plane sapphire. The realization of high quality semipolar GaN layers on m-plane sapphire is critical especially for LED device applications. GaN was grown on m-plane sapphire with HVPE [10], MOVPE [11,12] and MBE [13]. HVPE layers were smooth and single crystalline with $(2\bar{1}\bar{1}2)$ or $(10\bar{1}\bar{3})$ orientation. The $(10\bar{1}\bar{3})$ oriented layers grown by Matsuoka et al. by MOVPE were rough and twinned [11], whereas the MOVPE-grown $(2\bar{1}\bar{1}2)$ layers from Kappers et al. were smooth [12]. With MBE a polycrystalline mixture of $(10\bar{1}0)$ and (0001) GaN was observed. In this study the growth of semipolar GaN films by MOVPE is investigated: We were able to grow $(2\bar{1}\bar{1}2)$ and $(10\bar{1}\bar{3})$ oriented GaN layers in the same MOVPE-reactor. An addition to the epitaxial relationship of $(2\bar{1}\bar{1}2)$ oriented layers as described by Baker et al. [10] was found. The $(2\bar{1}\bar{1}2)$ GaN layers were analyzed for crystal quality, surface structure and photoluminescence properties.

2 Experimental GaN was grown on nominally on axis $(10\bar{1}0)$ m-plane sapphire in an Aixtron 2600G3 HT MOVPE reactor in 11x2" configuration. A two step growth was initiated by low temperature nucleation at 610 °C surface temperature (as measured by an EpiCurveTT in-situ

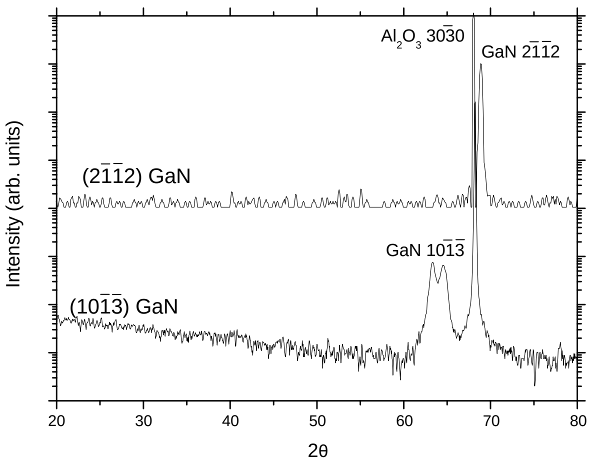

Figure 1 Symmetric $\omega/2\theta$ XRD scan around the $(30\bar{3}0)$ reflection of sapphire for the $(10\bar{1}\bar{3})$ and $(2\bar{1}\bar{1}2)$ samples.

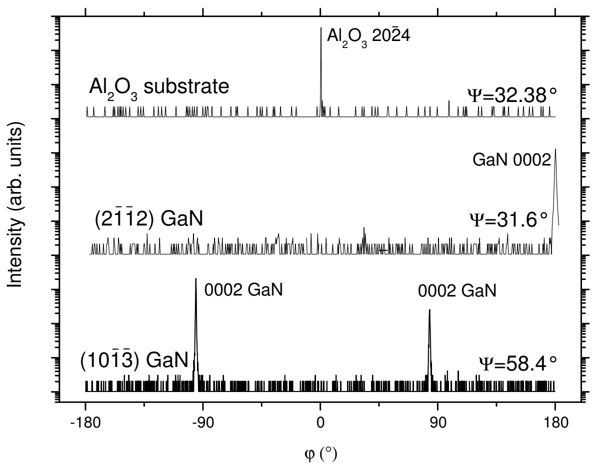

Figure 2 HR-XRD scan of the φ-axis with settings for the (0002) reflection ($\omega = 17.28°$; $2\theta = 34.57°$)

temperature, reflectivity and curvature sensor). Then a 1.8 µm thick high temperature (990 °C) buffer layer was grown at a rate of 2.5 µm/h. The growth pressure was 100 mbar.

Characterization of the samples by high resolution X-ray diffraction (HR-XRD) was performed using a Philips MRD and a Philips X'Pert Pro. Surface morphology was investigated by a Topometrix Explorer atomic force microscope (AFM). A HeCd laser at 326 nm was used for low temperature photoluminescence at 8 K. The laser focus has typically a diameter of 100 µm and a power density of about 20 W/cm^2 generating an excess carrier density of about 10^{16} cm^{-3}.

3 Results and discussion The growth on m-plane sapphire yielded $(2\bar{1}\bar{1}2)$ and $(10\bar{1}\bar{3})$ oriented layers (see Fig. 1).

3.1 Epitaxial relationship of $(2\bar{1}\bar{1}2)$ GaN The polarity of the GaN film can not be determined by XRD. In previous papers [10,12] the polarity of similarly grown samples was determined by convergent beam electron diffraction (CBED) to be Ga face, i.e. $(2\bar{1}\bar{1}2)$. We assume the same for our samples.

A tilt of $0.58{\pm}0.07°$ between $(2\bar{1}\bar{1}2)_{GaN}$ and $(10\bar{1}0)_{sapphire}$ towards $[0001]_{sapphire}$ was measured. The same tilt direction was found by Baker et al. although they measured a higher value of $1.8°$. The in-plane relationship was determined to be $[\bar{2}113]_{GaN} \parallel [0001]_{sapphire}$ or $[000\bar{1}]_{sapphire}$ (see Fig. 2). Both possibilities were observed: The orientation was stable over the 2" wafers, but varied from wafer to wafer. We assume, that the orientation is defined by a residual miscut of the nominal on axis wafers. The full width at half maximum (FWHM) of the rocking curve of the symmetric $(2\bar{1}\bar{1}2)$ reflection is 670" with incidence along $[0\bar{1}10]$ and 1590" with incidence along $[\bar{2}113]$. These values are comparable to values previously reported [12].

3.2 Epitaxial relationship of $(10\bar{1}\bar{3})$ GaN The growth of $(10\bar{1}\bar{3})$ was observed once as well, using the same recipe that yielded $(2\bar{1}\bar{1}2)$ GaN before (see Fig. 1). We assume the polarity to be the same as in HVPE growth studies of Baker et al. [4]. In their experiments both orientations, $(2\bar{1}\bar{1}2)$ and $(10\bar{1}\bar{3})$, occurred. The $(2\bar{1}\bar{1}2)$ orientation was observed, when the substrate was heated up in ammonia from room temperature and $(10\bar{1}\bar{3})$ orientation occurred if the ammonia valve was not opened until growth temperature was reached. In our experiments the $(10\bar{1}\bar{3})$ orientation occurred immediately after the change of the reactor ceiling. In the runs which yielded $(2\bar{1}\bar{1}2)$ orientation, the reactor ceiling was covered with a thin film of parasitic depositions. We conclude, that the parasitic depositions seem to influence the nucleation.

The in-plane epitaxial relationship was determined to be $[0001]_{GaN} \parallel [11\bar{2}0]_{sapphire}$ or $[0001]_{GaN} \parallel [\bar{1}\bar{1}20]_{sapphire}$. In Fig. 2 the φ-scan of the asymmetric (0002) reflection is shown: One peak is expected due to the symmetry of the crystal, like for $(2\bar{1}\bar{1}2)$, but two peaks are observed, i. e. the crystal is twinned. In HVPE, twinning did not occur [10], but in MOVPE (as observed here and by Matsuoka et al. [11]). This twinning can be explained by the epitaxial relationship of m-plane sapphire with $(10\bar{1}\bar{3})$ GaN: There are two alignment possibilities for $(10\bar{1}\bar{3})$ GaN seeds on m-plane sapphire. For growth on (100) spinel twinning was found in MOVPE growth, too, but not in HVPE growth [5,4]. It appears that nucleation in HVPE is more robust against twinning than nucleation in MOVPE.

3.3 Morphology To the eye the surface of the $(2\bar{1}\bar{1}2)$ layer is specular. With AFM (Fig. 3) a small scaled surface structure with a period of 400 nm and an amplitude of 25 nm was revealed. Root mean square (RMS) roughness over 10x10 µm^2 was 15.2 nm. The arrowhead shaped structures are aligned along $[\bar{2}113]$ and are inclined to the average sur-

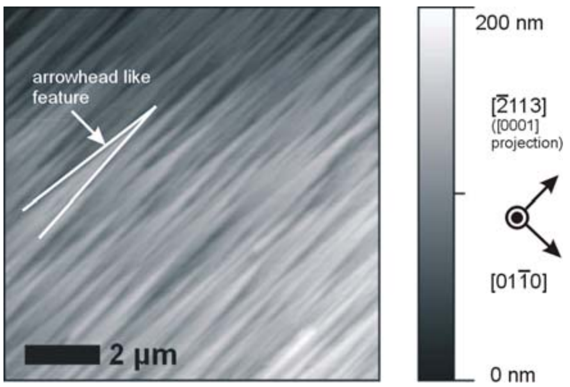

Figure 3 AFM micrograph of the surface structure of semipolar $(2\bar{1}\bar{1}2)$ GaN. Arrowhead like features point to the upper right of the picture.

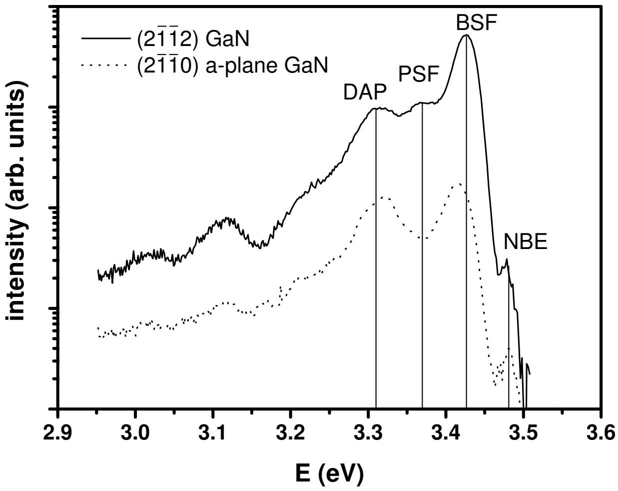

Figure 4 PL spectrum of $(2\bar{1}\bar{1}2)$ and $(2\bar{1}\bar{1}0)$ GaN. Identified peaks are labeled in the diagram.

face height by $0.4°$ to $0.9°$. The origin of this surface structure may be the tilt of $0.58°$ between the sapphire $(10\bar{1}0)$ and the GaN $(2\bar{1}\bar{1}2)$, that fits well to the inclination angle of the arrowheads.

The $(10\bar{1}\bar{3})$ sample was very rough: crystallite height and size were both in the order of micrometers. The rough morphology reflects the micro twinning of the sample.

3.4 PL on $(2\bar{1}\bar{1}2)$ GaN Fig. 4 shows the PL-spectrum of a semipolar $(2\bar{1}\bar{1}2)$ GaN layer. This spectrum is similar to spectra of a-plane GaN [14,15]. Several emission lines could be assigned according to the emission energies in literature: A near band edge (NBE) donor bound exciton (D^0,X) emission at 3.47 eV, emission from basal plane stacking faults (BSF) at 3.42 eV, prismatic stacking fault (PSF) related emission at 3.36 eV and donor acceptor pair (DAP) emission at 3.31 eV and corresponding phonon replica.

4 Conclusion

Semipolar GaN films were grown by MOVPE on $(10\bar{1}0)$ m-plane sapphire. The two step growth yielded specular $(2\bar{1}\bar{1}2)$ oriented GaN layers. Two possibilities for the in-plane orientation relationship were discovered: $[\bar{2}113]_{GaN}$ may be oriented along $[0001]_{sapphire}$ or $[000\bar{1}]_{sapphire}$. The surface had an arrowhead structure with a period of 400 nm aligned along $[\bar{2}113]$ with a RMS roughness of 15.2 nm, which we attribute to a tilt between GaN layer and sapphire substrate. The PL spectrum revealed the presence of stacking faults.

The growth of $(10\bar{1}\bar{3})$ GaN was observed using the same growth procedure. The change in orientation is attributed to a smaller amount of parasitic depositions in this particular growth process. The resulting layer was rough due to a large number of micro twins, as confirmed by XRD.

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