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Planar semipolar $(10\bar{1}1)$ GaN on $(11\bar{2}3)$ sapphire

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We report on the growth of planar semipolar $(10\bar{1}1)$ GaN on $(11\bar{2}3)$ prepatterned sapphire. This is a method that allows the growth of semipolar oriented $(10\bar{1}1)$ GaN on large scale. Using x-ray diffraction only the peaks of the desired $(10\bar{1}1)$ plane could be observed. Scanning electron, transmission electron, and atomic force microscopy measurements show an atomically flat surface. Further investigations using photoluminescence spectroscopy show spectra that are dominated by the near band edge emission. The high crystal quality is furthermore confirmed by the small full width at half maximum values of x-ray rocking curve measurements of less than 400 arcsec. © *2010 American Institute of Physics*. [doi:10.1063/1.3442484]

Devices like light emitting diodes (LEDs) based on GaN are usually grown in c-direction. Due to induced biaxial strain and the lattice geometry of group-III nitrides, huge piezoelectric fields are present within heterostructures along this particular direction. As result of this band bending there are some undesirable effects on the quantum wells (QWs) grown in that direction,[1] like spatial separation of the wave functions of electrons and holes. As consequence there is a reduced recombination probability (recombination rate) of LEDs, a redshift in the emission wavelength and a backshift to higher energies for higher drive current.[2] This is known as quantum confined Stark effect.

One possibility to reduce these negative effects is to grow in semipolar or nonpolar direction. Due to the lack of real bulk GaN substrates, nowadays these structures have to be grown on foreign substrates, and therefore, the research is still focused on the growth on different templates. Nonpolar GaN can be grown on several different foreign substrates but still suffers from a huge amount of stacking faults.[3–5] Various semipolar orientations of GaN have been also investigated on different substrates, like $(10\bar{1}1)$ GaN on silicon,[6] $MgAl_2O_4$,[7] or as facets grown on c-plane sapphire.[8] $(11\bar{2}2)$ GaN has been grown on m-plane sapphire[9] or on facets of c-plane oriented GaN stripes.[10] Just recently Okada *et al.* presented a method to grow $(11\bar{2}2)$ GaN on r-plane sapphire.[11] Another possible approach is to use sliced pieces from hydride vapor phase epitaxial grown material,[12,13] but these templates are quite expensive and very limited in size. Up to now the perfect substrate is still missing and therefore there is a lot of research in this context at the moment.

From this background, in this study, we propose the planar growth of semipolar $(10\bar{1}1)$ oriented GaN directly on sapphire in a similar approach as Hikosaka *et al.*[6] or Okada *et al.*[11] For this purpose the use of $(11\bar{2}3)$ sapphire seems to be appropriate as the inclination angle between $(0001)_{Al_2O_3}$ and $(11\bar{2}3)_{Al_2O_3}$ is nearly the same like the angle between $(0001)_{GaN}$ and $(10\bar{1}1)_{GaN}$. Calculations show that the piezoelectric fields within QWs grown in that direction will be drastically reduced when compared to c-plane growth.[14] Additionally, this surface is regarded as naturally stable facet since it exhibits an automatically formed and very smooth surface.[15] A higher indium incorporation is also observed, which can be advantageous for longer wavelength light emitters.[16]

The growth was carried out in a commercial horizontal flow Aixtron-200/4 RF-S reactor with the standard precursors trimethylgallium (TMGa), trimethylaluminum (TMAl), and high purity ammonia (NH_3). For the carrier gas we used Pd diffused hydrogen. The process temperature was controlled by a pyrometer at the backside of the rotation tray. As starting substrate lithographically structured $(11\bar{2}3)$ oriented sapphire was used with grooves along the in-plane m-direction. Therefore we deposited a 200 nm silicon dioxide (SiO_2) mask via plasma-enhanced chemical vapor deposition which also acts as a mask for the selective area growth. A 550 nm thick mask of nickel and gold, structured with a (3 μm opening)×(3 μm mask) stripe pattern was used for dry etching of the sapphire via reactive ion etching. To start growth we used an oxygen doped low temperature AlN nucleation layer,[17,18] followed by approximately 1 μm GaN with a V/III ratio of 650 at a temperature of 1130 °C and a pressure of 150 hPa.

To characterize the samples and their crystal quality we used x-ray diffraction (XRD) rocking curve measurements (XRC) and ω-2θ scans as well as low temperature (14 K) photoluminescence (PL) measurements. Particularly, the latter enables us to judge about typical defects in semipolar and nonpolar GaN layers, like basal plane stacking faults (BSFs).[19] The surface quality could be accessed via scanning electron microscopy (SEM), transmission electron microscopy (TEM), optical phase contrast microscopy (OM), and atomic force microscopy (AFM).

Figure 1 shows the growth principle. The GaN growth starts from the groove facets of the sapphire wafer in the usual c-direction, which has a certain inclination to the surface [Fig. 1(a)] resulting in a flat and planar semipolar layer [Fig. 1(b)]. The crystal orientation was measured via a symmetrical XRD ω-2θ-scan (Fig. 2). The sapphire substrate

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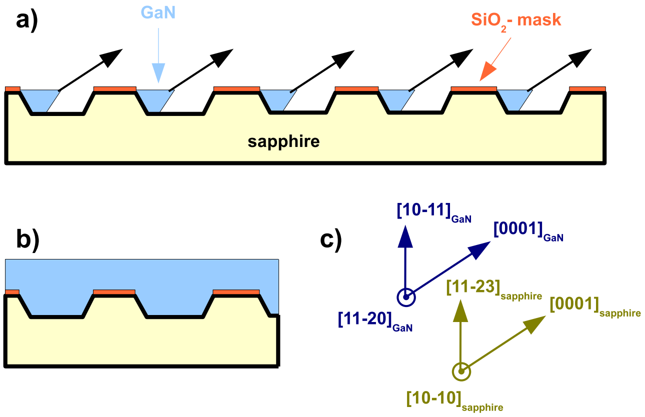

FIG. 1. (Color online) Schematic figure of the principle idea. (a) Grooves were etched into $(11\bar{2}3)$ sapphire, the growth starts at the sidewalls in c-direction. (b) The GaN islands coalesce, resulting in a planar semipolar $(10\bar{1}1)$ GaN layer. (c) The crystal orientations of the sapphire and the semipolar GaN.

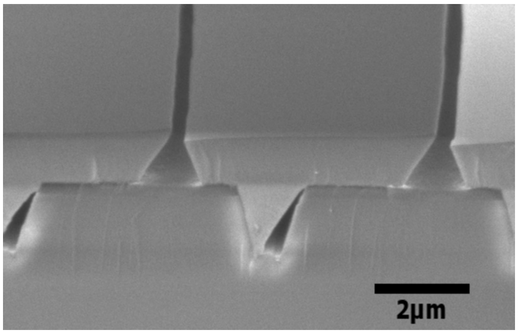

FIG. 3. SEM micrograph of the cross-section of the sample. The crystal orientations are the same as sketched in Fig. 1(c).

peaks and the $(10\bar{1}1)$-reflection of GaN are clearly visible; no other crystal orientation could be observed. Additionally, the skew geometric (0002) peak of GaN and the (0006) reflection of sapphire appear at the same φ-angle (rotation around the surface normal) and at the expected χ-angle (rotation around the cut of the surface with the scattering plane) [not shown]. Therefore we conclude an orientation of the GaN film as sketched in Fig. 1 with a semipolar $(10\bar{1}1)$ surface. The in-plane orientations were investigated by selected area electron diffraction of cross-section samples and were found to be $[0001]_{\mathrm{GaN}} \| [0001]_{\mathrm{sapphire}}$ and $[11\bar{2}0]_{\mathrm{GaN}} \| [10\bar{1}0]_{\mathrm{sapphire}}$.

The SEM micrograph (Fig. 3) reveals the morphology of the sample. The GaN starts to grow within the grooves of the prepared sapphire substrate. As proposed, this happens only on the c-plane like side-facet of the trench, resulting in growth directed exclusively in c-direction. Although a complete nucleation layer was deposited, no growth took place on the SiO_2 covered ridges. This area could be overgrown comparable to the well known epitaxial lateral overgrowth principle when the GaN reaches this height and is able to grow more in lateral direction. The wing tilt of the overgrown area is about 0.2°, as visible in XRD measurements. Additionally, the excellent surface quality was confirmed by AFM and TEM measurements (Fig. 4). The root mean square roughness determined by AFM was as small as 0.1 nm for a 1×1 μm^2-scan and below 0.3 nm for a 3×3 μm^2-scan, respectively. An atomically flat surface was found by high resolution (HR)-TEM investigations.

The high crystal quality was verified by narrow XRC peaks. The full width at half maximum of both, the symmetrical $(10\bar{1}1)$ reflection and the asymmetrical (0002) and $(10\bar{1}2)$ reflections were smaller than 400 arcsec, respectively. Furthermore, the low-temperature PL-spectra (Fig. 5) revealed a comparably strong and dominating near band edge emission (NBE) at 3.464 eV. Typically in semi- and nonpolar GaN grown on sapphire this luminescence is quite weak and the defect correlated luminescence is dominating. Nevertheless some of the typical defect related peaks are also visible in our sample. The transition around 3.43 eV, which can be attributed to BSFs,[20] could not be suppressed completely. Also, the lower energy peaks (around 3.30 eV), usually assigned to (pyramidal) stacking faults (and partial dislocations)[21] are still visible. Performing TEM investigations the local distribution of stacking faults could be investigated (not shown). The highest density of stacking faults can be found in the −c-wing, the +c-wing of the laterally overgrown area provides the lowest density. This area might be further increased and the defect density decreased by adequate growth conditions.

In summary planar semipolar $(10\bar{1}1)$ GaN on $(11\bar{2}3)$ prepatterned sapphire was grown. This method allows large area growth of semipolar oriented $(10\bar{1}1)$ GaN on sapphire. Compared to other growth techniques and the resulting qual-

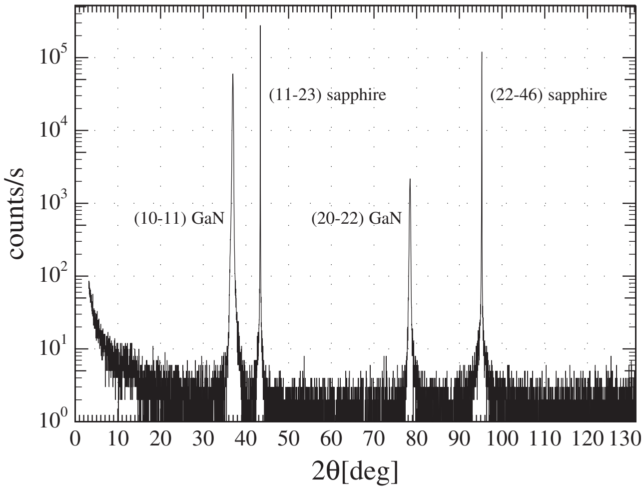

FIG. 2. XRD ω-2θ scan showing the peaks of $(11\bar{2}3)$ sapphire and $(10\bar{1}1)$ GaN (plus second order peaks). No other peak owing to another orientation of GaN is visible.

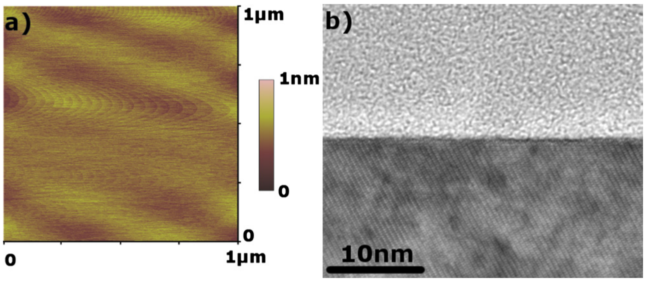

FIG. 4. (Color online) (a) AFM image of the GaN surface. The size is 1×1 μm^2. The rms roughness is below 0.1 nm. (b) HR-TEM image of a cross-section showing the homogeneity and high quality of the surface.

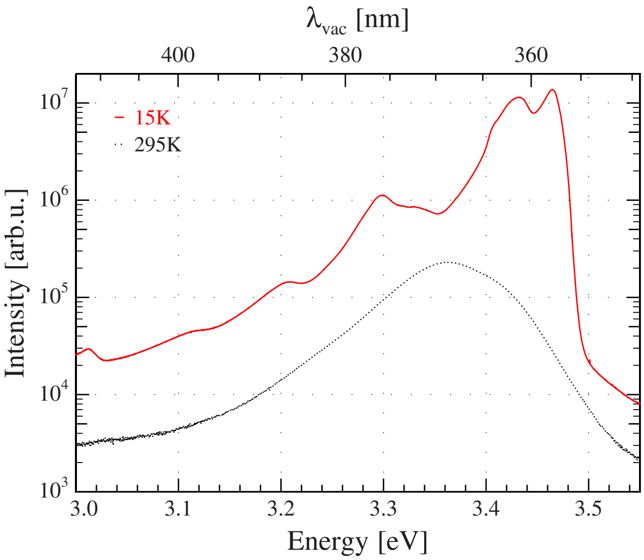

FIG. 5. (Color online) PL spectra recorded at low temperature (15 K). Visible are the NBE as dominant peak (3.464 eV) and some defect related emission lines (e.g., 3.430 or 3.300 eV).

ity of nonpolar GaN on sapphire this approach is quite promising, in particular if further optimization steps are included.

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