Epitaxial growth and characterization of deep UV AlGaN devices on bulk AlN substrates

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Bulk AlN crystals are considered the most promising substrate material for UVC LEDs or laser diodes (LDs) based on $Al_xGa_{1-x}N$ layers with high Al content. The use of epi-ready and deep UV transparent AlN substrates with high crystalline perfection is considered a prerequisite for the realization of deep UV emitters with high internal quantum efficiencies (IQEs). In this work, we will present the entire processing-chain from the growth of deep UV transparent AlN single crystals to the optical characterisation of the UVC LED heterostructures.

We demonstrate that highly deep UV transparent AlN crystals ($\alpha_{265nm} < 15$ cm^{-1}) can be grown by physical vapor transport (PVT) when impurity concentrations of oxygen and carbon satisfy the following inequalities: $3[C] < [O]$ and $([C] + [O]) < 10^{19}$ cm^{-3}. Epi-ready Al-polar c-AlN substrates are prepared by using a qualified chemo-mechanical polishing (CMP) process. Transmission and back-reflection topographs of the substrates reveal TDD < 10^4 cm^{-2} over the entire area of the Ø10 mm substrates. No residual polishing-induced subsurface damage is visible in the topographs. The accuracy of the wafer orientation reliably achieves a miscut < 0.2° ensuring long terrace widths of the step flow when growing epitaxial layers.

Overgrowth of the epi ready Al polar (0001) AlN surfaces by metalorganic vapour phase epitaxy at 1250°C leads to a homogenous continuation of the AlN growth. XRD rocking curves do not exhibit additional or broadened peaks and no defects are observed at the interface by TEM. The morphology depends strongly on the miscut angle and exhibits step smooth step flow morphology for a miscut < 0.2° and step bunching for a miscut > 0.2°.

Optically pumped laser structures were grown on the bulk AlN substrates. The laser heterostructures consist of 3 nm $Al_{0.7}Ga_{0.3}N$ / 8 nm $Al_{0.82}Ga_{0.18}N$ triple quantum wells embedded in between two 28 nm thick $Al_{0.82}Ga_{0.18}N$ waveguide layers and were capped with 75 nm of AlN. Laser scribing and cleaving was performed in order to obtain smooth facets for edge emission. Optical pumping with an 193 nm ArF excimer laser focused into a 15 µm x 1000 µm stripe results in lasing at 242 nm with a narrow spectral line width of 0.9 nm.

UVC-LED heterostructures with emission at 269 nm employing UV-transparent p-AlGaN were grown on the UV transparent bulk AlN substrates. Dominant AlGaN quantum well emission was observed from UVC-LEDs even through a 600 µm thick AlN substrate. The LEDs were processed by standard lithography and metallization and tested on wafer. By ray-tracing, extraction efficiencies in dependence of the substrate thickness were calculated. Possible reasons for the not fully exploited EQE, like non-radiative recombination on point defects and light extraction efficiency (LEE) issues, are discussed.

In summary, we have demonstrated the growth and preparation of an UV transparent AlN bulk substrate that is suitable for the growth of UVC lasers and LEDs.

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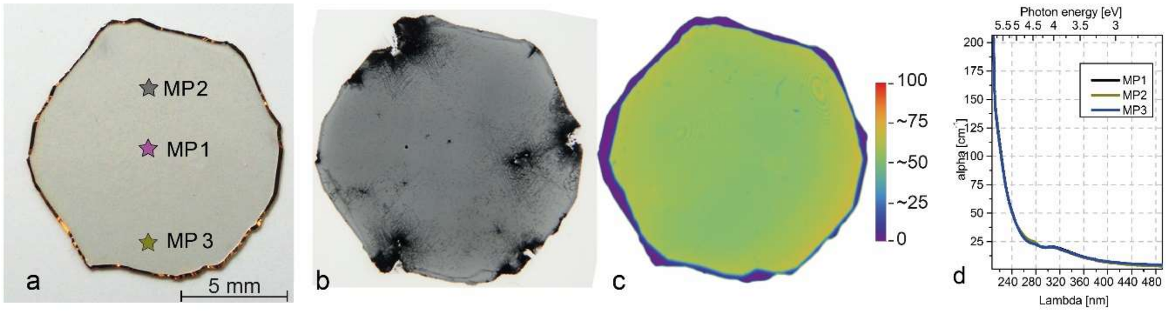

Fig. 1: (a) image of a c-plane AlN substrate wafer with highlighted measuring spots; (b) transmission X-ray topograph of the same c-plane wafer; (c) transmittance of this wafer at 254nm (wafer thickness = 140 µm), (d) absorption spectra at highlighted measuring spots (α_{265nm} = 25 – 28 cm^{-1})

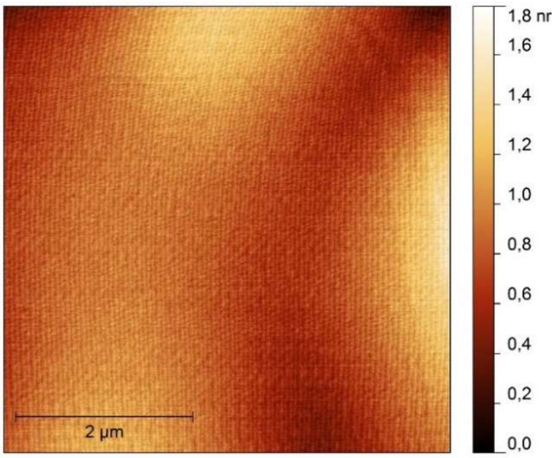

Fig. 2: 10x10 µm AFM of an MOVPE-grown AlN layer on AlN bulk substrate exhibiting smooth step flow growth with RMS of 0.22 nm.

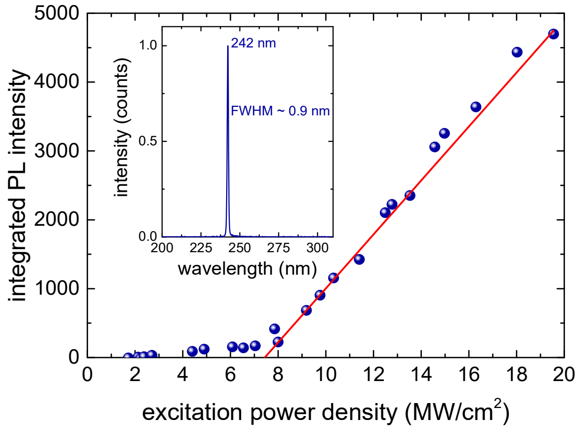

Fig 3: Integrated peak intensity measured from the facet of a laser heterostructure grown on bulk AlN over the optical pumping power. The inset shows the laser spectrum above threshold.

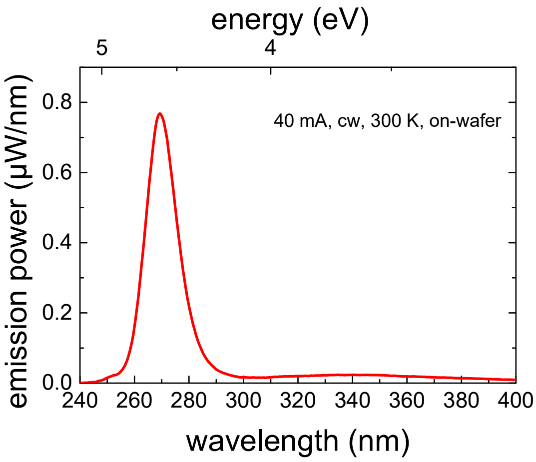

Fig. 4: Electroluminescence spectrum of a MOVPE-grown UVC LED emitting at 269 nm measured through the 600 µm thick AlN substrate.