In-situ metrology solutions for UV LED growth

The new Gen3 generation of in-situ metrology offers pyrometry up to 1500 °C, precise reflectance for AlN/AlGaN analysis, high precision material database and many more advanced features.

Epitaxial growth of UV LEDs faces significant challenges: long runs, superlattices, high Al content vs. high doping level, very high growth temperature, large wafer bow and many more. In-situ metrology is the key to solve most of these problems. Here are some application examples.

Fig. 1 shows a layer stack of a typical UV LED structure to illustrate the growth steps monitored by LayTec's EpiTT Gen3 in Fig. 2.

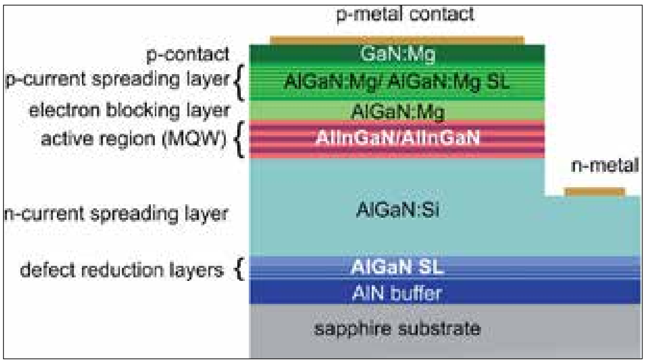

Fig. 1: State-of-the art UV-LED design according to [1]

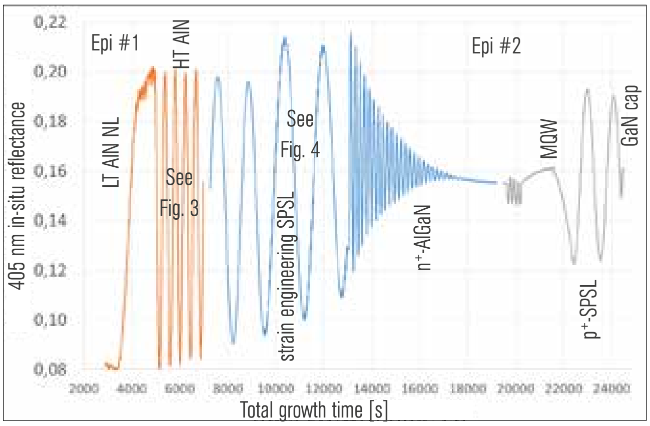

Fig. 2: Two step MOCVD growth of UV-B LED (305 nm): 405 nm in-situ reflectance monitored by EpiTT. (HT=high temperature, LT=low temperature, NL=nucleation layer, SPSL=short-period superlattice)

In the course of LayTec's cooperation within the consortium "Advanced UV for Life" (supported by BMBF, grant number 03ZZ0105C), scientists of Technical University of Berlin and FBH (Berlin, Germany) have developed a high temperature MOCVD process for growing low-defect-density AlN/sapphire templates for UV LEDs. The split of the UV LED growth in two separate steps in two different MOCVD systems fully avoids the possible memory effect related interference of AlGaN processes with the growth of high quality AlN buffers.

Benefits:

- Optimization of UV LED epitaxy
- Early detection of process deviations and wafer defects
- Higher yield
- Better uniformity
- Excellent device performance

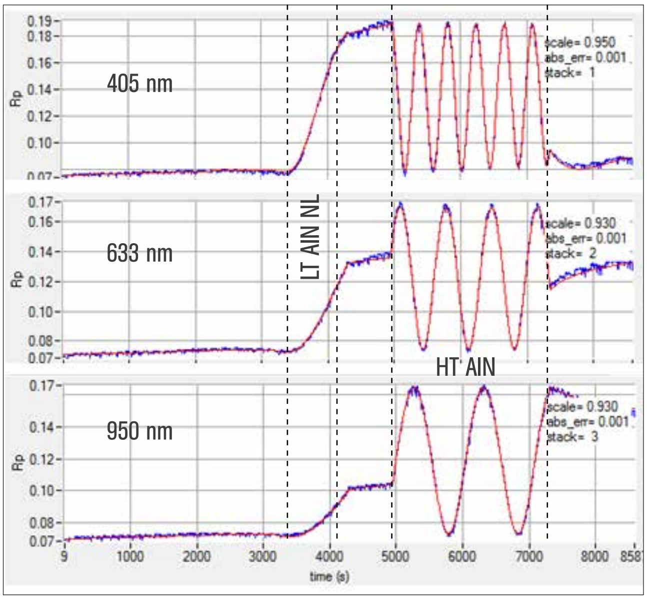

Fig. 3: In-situ reflectance at 405 nm, 633 nm and 950 nm of the two step growth of an AlN template structure for UV LEDs monitored: Blue curves - measured data, red curves - fitted data.

The AlN buffer growth (Fig. 3) was monitored by 3 wavelength reflectance improved for very thick AlN/AlGaN layer stacks and by the emissivity corrected high temperature sensing of EpiTT Gen3. The blue curve is the result of the quantitative analysis of the 3 wavelength reflectance measured by EpiTT Gen3. The thickness of the AlN nucleation layer is determined from the fitting curves (red) to be 43.2±0.2 nm, and the AlN high temperature buffer layer thickness to be 524.2±0.5 nm. The consistency of the used high temperature nk database is also obvious from the good agreement of the simulated curve segments in the temperature up-ramping and down-cooling steps.

The key for the unrivaled EpiTT Gen3 high temperature performance is not just the widened temperature sensing range, but also the high temperature nk database (up to 1500 °C) for the AlN and AlGaN class of materials and improved performance for double-side polished sapphire wafers.

Alongside with temperature and reflectance, in-situ wafer bow monitoring by EpiCurve® TT Gen3 is a further pathway to process and reactor optimization. Fig. 4 reveals the intrinsic challenge of AlN buffers for UV LED yield: the wafer bow at the growth temperature of active region (T_{MQW}) is always large, which finally leads to non-uniform UV-LED emission wavelength and, as a result, to lower yields. One of the methods to reduce the strain and annihilate dislocations is a short-period superlattice (SPSL) of GaN/AlN. Internal GaN/AlN interfaces are the key for reducing dislocation density. In-situ reflectance at 405 nm in Fig. 5 directly shows the formation of these 160 interfaces between the ~1nm thick GaN/AlN layers. Ex-situ measurements in Fig. 6 confirm this.

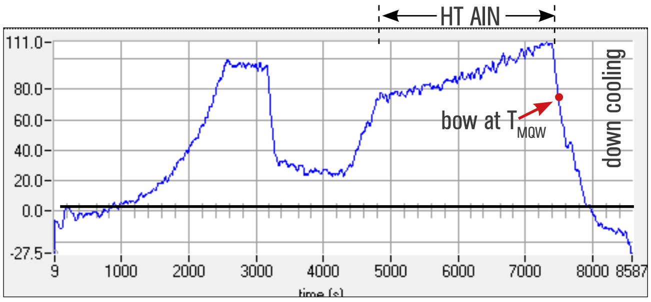

Fig. 4: In-situ wafer bow measurements during growth of UV LED structure.

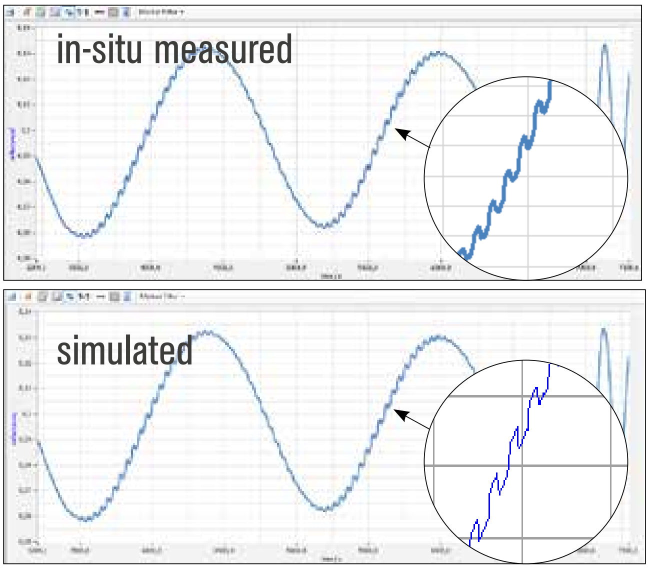

Fig. 5: 405 nm reflectance measured in-situ (above) and simulated (below). The inserts magnify in-situ response to the formation of GaN/AlN interfaces of SPSL.

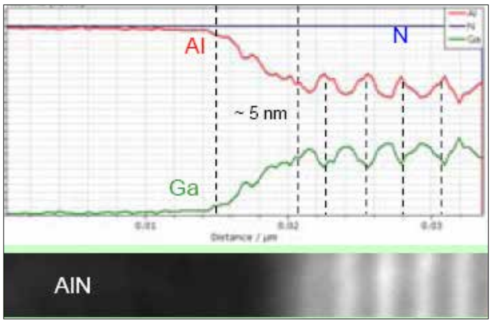

Fig. 6: Ex-situ data: transition from AlN buffer to GaN/AlN superlattice. [2] Red - Al, green - Ga, blue - N.

280 nm reflectance for AlGaN surface morphology and growth rate

AlGaN buffer layers with high Aluminum content are necessary for optimal UV-C LED performance. But their band edge lies below 300 nm, so, the established 405 nm in-situ reflectance is insensitive to the surface morphology of such AlGaN layers. To monitor precisely both AlGaN growth rate and surface morphology during UV-C LED epitaxy, LayTec offers an additional 280 nm reflectance channel that employs a UV-C LED as a light source. Fig. 7 shows the results measured in-situ during the growth of an AlGaN layer: The Fabry-Perot oscillations of the final AlGaN layer are damping out because the band edge of the material shifts toward longer wavelength at the growth temperature. The small reflectance reduction at 12000 s indicates a small roughening of the AlGaN surface. The short-period superlattice (SPSL) interface signatures are also clearly resolved in the 280 nm reflectance.

The green line delivers the high-resolution wafer bow data: at ~1000 s the strain changes from compressive towards tensile during AlGaN growth. The wafer bow signal also demonstrates that the latest EpiCurve® TT Gen3 in a Close Coupled Showerhead® (CCS) reactor has a significantly improved curvature resolution of 0.3 km^{-1}. With this improvement, in-situ strain balancing or AlGaN lattice constant tuning is now possible with accuracy levels formerly known only for ex-situ XRD methods.

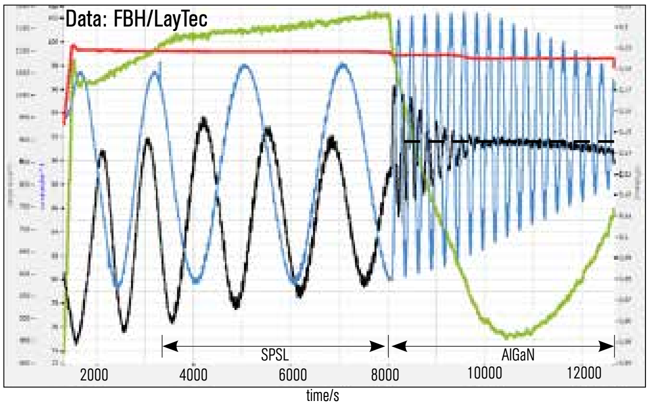

Fig. 7: Growth of AlN/AlGaN(60%Al) on a Sapphire/AlN template in Aixtron CCS 6x2 reactor: black – 280 nm reflectance; blue – 405 nm reflectance; green – high-resolution wafer bow; red – true temperature.

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Accurate temperature for pss and double-side polished sapphire in UV LED growth

For UV LEDs, the emitted light usually exits the device structure through the sapphire substrate. Therefore, double-side polished (dsp) sapphire is frequently used. In addition, the front surface of the sapphire substrate can be modified by nano-patterned sapphire substrates (pss) for enhanced light extraction. Both substrate specifics often cause unrecognized artifacts in temperature sensing.

As an example, Fig. 8 shows a temperature step run with three different types of sapphire substrates: dsp, pss and ssp (single side polished). Conventional IR (infrared) pyrometry (Fig. 8a) measures three different pocket temperatures for these wafer types. While the dsp sapphire substrate at 900 °C gives the correct value, ssp is ~10 K and pss is ~25 K less than dsp. The level of the apparent (but not real) temperature reduction depends on temperature and on the details of back-side roughening, pss patterning and reactor configuration. EpiTT Gen3, however, comes with new software algorithms that take these specific effects into account and deliver the same accurate pocket temperature for ssp, dsp and pss sapphire substrates (Fig. 8b).

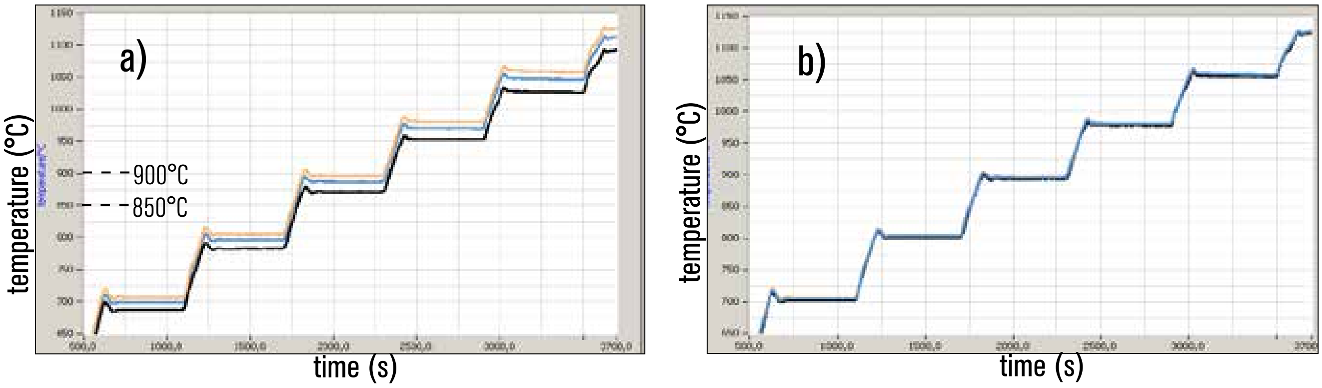

Fig. 8: Temperature step run. True Temperature at 950 nm: blue - pocket W5 (ssp), orange - pocket W6 (dsp), black - pocket W8 (pss).
a) measured by a conventional emissivity corrected IR pyrometer; b) measured by EpiTT Gen3, which eliminates emissivity effects and straylight/defracting effects of the wafer's backside and/or of the pss frontside.

Overcoming the wafer-showerhead gap variation in UV LED epitaxy

For UV LED processes, EpiTT Gen3 can measure temperatures up to 1500 °C. However, a further new Gen3 feature is also of importance – the possibility to choose between two types of metrology heads (see Fig. 9): fiber-optical heads (FOHs) and the new parallel-beam heads (PBHs). The latter is the tool of choice, e.g., for customers with Close Coupled Showerhead (CCS) reactors who frequently adjust the wafer-showerhead gap to avoid pre-reactions and achieve high growth rates in UV LED processes.

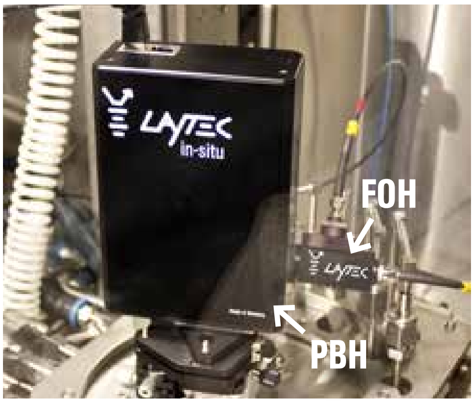

Fig. 9: EpiTT Gen3: the user can choose between a parallel beam head (PBH) and a fiber optical head (FOH - on a viewport behind PBH).

Fig. 10 shows that FOHs suffer from the off-focus situation, which has to be compensated by multiple-gap calibration, while PBHs deliver a very stable reflection and temperature signal despite the gap variation.

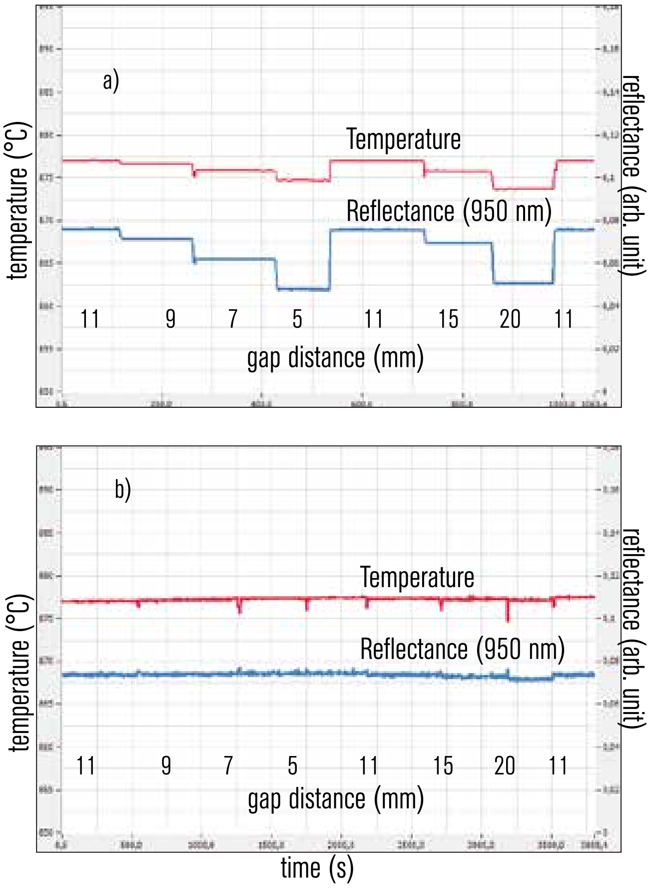

Fig. 10: Reflectance (950 nm) and temperature data during variation of gap size: a) FOH shows a reflectance drop of ~30 % with respective temperature drop of several Kelvins depending on sample structure b) PBH delivers a stable reflectance and temperature signal. At the standard gap distance (11 mm), both heads measure the same reflectance. (Data measured with an AbsoluT thermal reference.)

Summary:

LayTec and its R&D partners have delivered with EpiTT Gen3 and EpiCurve®TT Gen3 state-of-the art in-situ metrology for UV LED related MOCVD. This metrology is a must for process development and for control of such complex devices as UV LEDs. For further information please visit www.laytec.de/UVLED or contact info@laytec.de.

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[1] N. L. Ploch, Chip designs for high efficiency III-nitride based ultraviolet light emitting diodes, PhD thesis, Technical University of Berlin 2015

[2] A. Mogilatenko *et al*, Investigation of AlN/Al,Ga)N superlattices grown on high-temperature AlN layers on sapphire by metalorganic vapour phase epitaxy, poster, Humboldt University of Berlin 2009

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