Growth of LED Structures on 6 inch Sapphire: Challenges and Improvements

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Abstract

Energy saving has become a strong global strategy. As one example for lighting the use of white-light LEDs has enabled the industry to take giant steps in this regards due to low energy consumption, robust behaviour and slim-line design in comparison to conventional light sources. This offers completely new pathways of devices and applications from both a performance as well as cost reduction perspective. This paper presents pathways to overcome challenges for deposition of generic LED structures on large 6 inch diameter sapphire substrates taking advantage from calculations based on modeling prior to experiments as well as from in-situ measurements. Results from wafers prepared accordingly will be presented as well.

MOCVD: Contribution for Cost Reduction

As the major request to further pave the path for implementation of LEDs as generic devices for lighting the cost per lumen still has to be reduced. For example, "Haitz' law" requests the cost per lumen to be reduced by a factor of 10 per decade while, at the same time, the flux per package to be increased 20 times. The MOCVD (Metal-Organic Chemical Vapour Deposition) technology as one of the production steps to manufacture LEDs is able to contribute to this requirement by increasing the total wafer/substrate area being deposited during one epitaxial run using comparable process conditions and, thus effectively reducing the consumption of raw materials per unit wafer area. As a reference, switching from a configuration of 42x2 inch wafers (total area: 851.27 cm^2) to 6x6 inch (total area: 1,094.49 cm^2) for an MOCVD production equipment, an increase of 28.6% is achieved. Also, operator time and efforts are saved along the device processing line handling 6 wafers vs. 42. As sapphire substrates of 6 inch in diameter are becoming available in reasonable numbers today, MOCVD processes have to be adjusted and optimized to allow highly efficient and very uniform LED-structures to be produced under mass production conditions.

Simulation: Support for Process Optimization

InGaN/GaN structures as the basic material for white LEDs demonstrate different lattice parameters and thermal expansion coefficients in comparison to the sapphire substrate. Stress and strain in the course of the deposition itself as well as for the final epitaxial wafer at room temperature have to be considered. This challenge is becoming more significant for 6 inch wafers in comparison to related adjustments before in the past changing from 2 or 3 inch to 4 inch. To decrease the time to market taking the new development into account and to reduce the number of costly epitaxial test runs, simulations on varying process conditions and related results for single and stacks of layers as well as the complete layer structure were carried out.

Experiments and Results for AlGaN

The experiments were performed using a production type tool for layer deposition by MOCVD (model: AIX 2800G4 HT Planetary Reactor®) using the 6x6 inch configuration, each wafer being placed in the recess of a rotating substrate holder (satellite). All six satellites in conjunction with the large main disk, also rotating, demonstrate the so-called planetary set-up.

AlGaN layers are used for LED structures for different purposes (see Figure 1): i) $Al_{0.30}Ga_{0.70}N$ (and up to 50% Al) to reduce stress and strain between the GaN buffer and the sapphire or for growth of HEMT structures on silicon as the substrate, or ii) $Al_{0.18}Ga_{0.82}N$ as electron blocking layers between the MQW and p++ contact layer, just to mention two applications.

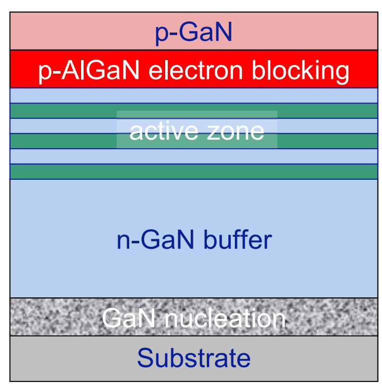

Figure 1: Example of a generic LED structure with n-GaN buffer, active zone with multi-quantum well structure, p-type AlGaN electron blocking layer and upper p-GaN.

Lower total process pressures (20 to 50 mbar) have been used in the past to provide, e.g., best achievable uniformities for layer thickness and/or composition. Investigations in recent years revealed that an increase for the total pressure leads to improved crystal quality.

A commonly observed disadvantage for Al-containing materials at higher pressures (50 to 100 mbar) is a more pronounced rate of pre-reactions due to higher collision probability between the source materials TMAl and NH_3, which leads to adducts and particle generation leading to a) defects on the epitaxial wafers, b) reduced efficiency for source materials due to this parasitic growth, and c) less incorporation of Al as well as non-uniformity for composition across the wafers.

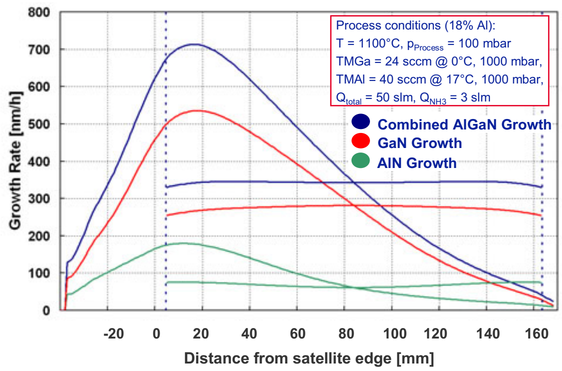

Figure 2: Simulation of super-positioning of AlN and GaN for AlGaN growth

Detailed simulations on improved hardware design for injection of the various source materials and process parameters were performed first super-positioning GaN and AlN as shown on Figure 2. Subsequent investigations supported to establish conditions for material quality as reflected in Figure 3. Very uniform Al-composition for 18% and 50% Al across the 6 inch wafer was found.

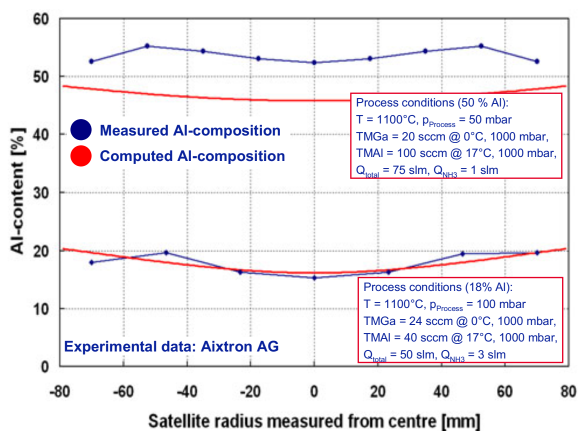

Figure 3: Comparison of simulation to experimental data for AlGaN compositional uniformity across a full 6 inch wafer

Bow: Curvature Measurement and Impact of Substrate Thickness

For growth of GaN buffers and InGaN/GaN MQWs as part of generic LED test-structures (see Figure 1) changing lattice parameters and thermal coefficients have to taken into account when considering optimization of stress reduction. Otherwise, bow will lead to epitaxial wafers with unacceptably low yield for further processing due to breakage (photo-lithography, adding contacts, cutting/dicing, handling in general, etc.).

Based on experience from up-scaling from 2 inch to 4 inch diameter it can be concluded that the larger the diameter the more challenging wafer bending compensation is considered to be. Based on pre-calculation in general similar to those mentioned for Al-containing layers before, substrates with thickness of 1.0 mm and 1.3 mm were used for further investigations on the larger size wafers.

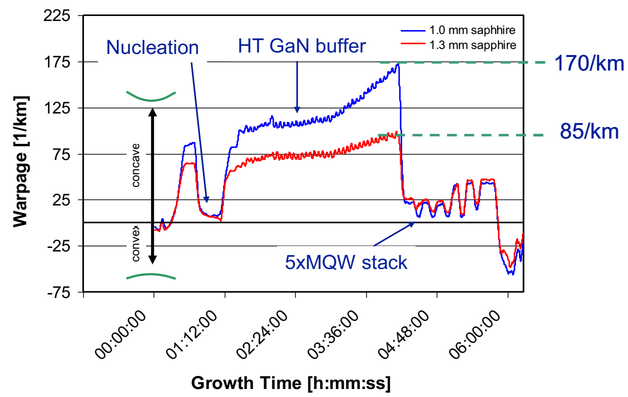

Figure 4: Curvature measured using an in-situ deflectometer for a whole MQW process on substrates of different thicknesses

In-situ curvature measurements from a 2 beam deflectometer revealed considerable differences in the bow for the HT (High Temperature) GaN buffer, i.e. 170/km curvature for a 1 mm and 85/km for a 1.3 mm thick substrate, respectively (see figure 4). This clearly indicates that a thicker substrate is more resistant to bow. At MQW growth conditions at lower temperatures the bows of the two wafers are reduced and more similar. The reason for this better consistency between both wafers is not clear, yet; different substrate quality may be a reason for this behaviour.

Photoluminescence Measurements

Photoluminescence measurements underline the better results for the thicker substrate comparing the better uniformity wavelength standard deviation σ_λ of 2.4 nm for a wavelength mean value λ_{mean} of 449.4 nm vs. σ_λ = 2.8 nm at λ_{mean} = 452.9 nm for the thinner wafer (see figure 5). Further results will be presented.

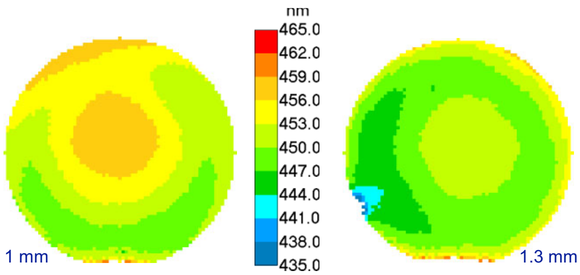

Figure 5: PL maps of MQW structures on 6 inch wafers of different thicknesses

CONCLUSION

Results from growth of generic LED structures on 6 inch sapphire substrates confirm that process conditions for an MOCVD system can be fine-tuned to match and even improve state-of-the-art specifications as are known from 2 inch, 3 inch, and 4 inch wafers in the past. Process simulation beforehand and curvature measurement during growth provide strong support for parameter optimization to speed up time to market related to different wafer sizes and configurations for an MOCVD production equipment.

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ACRONYMS

HT: High Temperature
LED: Light Emitting Diode
MOCVD: Metal-Organic Chemical Vapor Deposition
MQW: Multi-Quantum Well
TMAl: Tri-Methyl-Aluminum
TMGa: Tri-Methyl-Gallium