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Use of In-Situ Deflectometer Metrology for GaN MOCVD Reduces Development Time and Optimizes Product Yield

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SUMMARY

This application note examines how integrating multi-sensor in-situ metrology can be used to optimize HB-LED performance and production yields. We examine combining Deflectometry, Reflectometry and Temperature (DRT) measurements during MOCVD Gallium Nitride (GaN) growth runs to achieve highly uniform and repeatable growth cycles.

INTRODUCTION

It has long been acknowledged that metrology is fundamental to increasing yields in MOCVD processes. A controlled and predictable process delivers better device bin-sort, faster ramp to production, and sustained higher product yields.

To help advance the application of in-situ metrology for multi-wafer GaN systems, Veeco has launched the TurboDisc® DRT™ 210 In-Situ Process Monitor for the TurboDisc MOCVD GaN platforms.

The DRT-210 adds in-situ deflectometry to the mature RealTemp® metrology product line. The deflectometer provides accurate and direct measurement of the wafer curvature as it changes in real time due to deposition of the GaN epitaxial layers. The data is presented to the user via the integrated software platform and enables rapid implementation of process adjustments to maximize device performance.

Prior to the DRT-210 there was no real-time method to characterize the wafer curvature that can be induced by growth process variables. This paper will demonstrate that, while variations in process temperature can be a dominant contributor in controlling substrate curvature, more subtle variables such as buffer layer thickness and buffer layer doping can also be characterized and then tuned to control wafer curvature throughout the growth process.

Combining the measurements of wafer curvature, growth rates, and process temperature, Veeco provides users of MOCVD epitaxial growth equipment with the ability to obtain one more level of critical process data and new levels of process control.

In this paper we will review:

- The DRT-210 measurement and control capability
- Interaction between wafer curvature and yield
- The effectiveness of using in-situ deflectometry metrology to affect process change.

DRT-210: MEASUREMENT AND CONTROL

In the past, ex-situ characterization was performed after multiple growth layers inside the reactor. Process engineers could not correlate process temperature data to precisely where and when the wafer curvature exceeded desired wafer curvature parameters. As a result, multiple process adjustment and growth run iterations were required to ramp yields to the highest levels.

As shown in Figure 1, wafer curvature is measured by laser beam deflection. The deflectometer measures the intensity and position of laser light reflected from the wafer substrate as it moves underneath the detector at rotation rates between 260 and 1500 revolutions per minute (RPM).

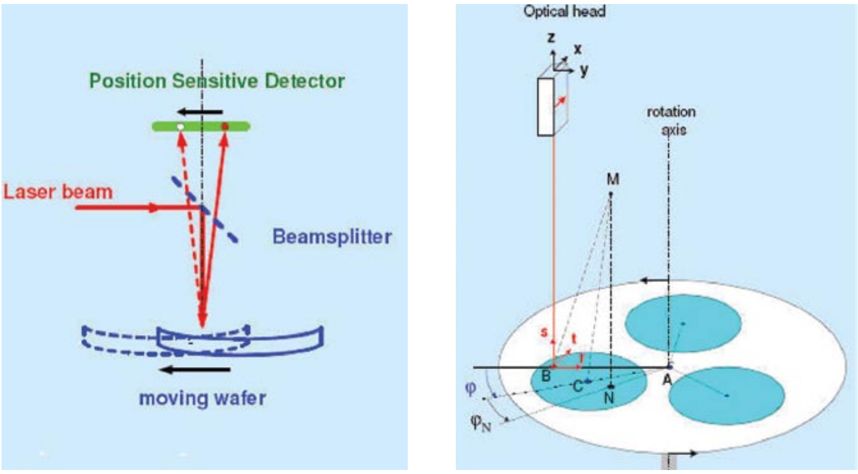
The shift in beam position, as a function of the wafer surface position and wafer shape (convex, flat, or concave), is measured in extremely precise time intervals. This provides direct, repeatable measurements which are then stored and displayed to provide an accurate real-time representation of wafer substrate curvature.

The stored wafer curvature data is time stamped for correlation with the process temperature and reflectivity measurements simultaneously obtained with the DRT-210.

Figure 2 illustrates in-situ metrology results from an MOCVD reactor equipped with the DRT-210. The full range of GaN epitaxial processes are depicted: annealing, nucleation, recovery, bulk n-GaN, InGaN multi-quantum well (MQW), and GaN barriers. Each plot within the chart represents one of the three measured data sets during GaN epitaxial growth on a 2-inch sapphire wafer. Wafer curvature is the line plotted in black, wafer reflectivity (for tracking epitaxial growth rate) is the line plotted in blue, and wafer temperature is the line plotted in red. The chart base also offers a graphic depiction of curvature change over time. Note that wafer curvature during recovery phase is recorded but is beyond depicted scale limits. Adjacent to the chart is a schematic depicting typical LED epi-layers.

FOCUS ON MULTI-QUANTUM WELLS

Throughout the MOCVD GaN growth steps, the high process temperatures, together with crystal lattice mismatch, induce mechanical strain (bow) within the substrates. Although all stages of the GaN epitaxial process impact yield, the multi-quantum well (MQW) layering process is the most crucial.



- The Position Sensitive Detector (PSD) measures the intensity and position of a reflected laser beam.
- The position of the reflected beam at the plane of the detector depends on the surface local tilt angle.
- As the wafer passes through the beam, the angular profile as a function of wafer displacement is measured, and therefore wafer curvature can be calculated.

Figure 1

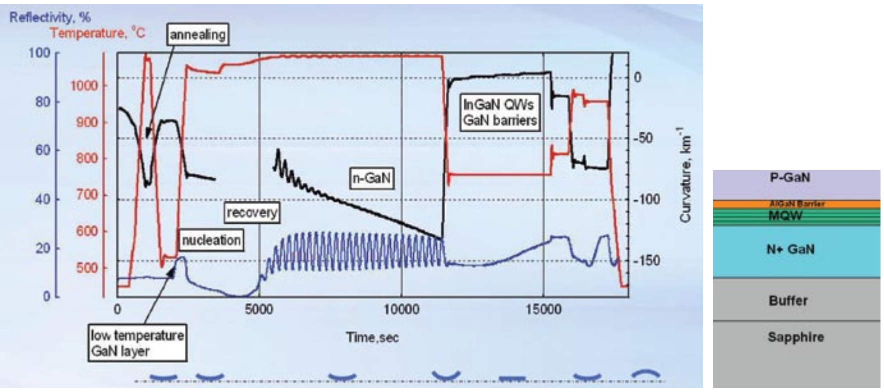


Figure 2. Example of integrated curvature, reflectivity and temperature during GaN epitaxial growth on Sapphire. The schematic depicts the LED epi-layers of the GaN epitaxial process.

Controlling the wafer curvature during the MQW growth steps to nominally match the wafer carrier pocket curvature is essential to achieving maximum thermal uniformity during growth and thus maximum wavelength uniformity throughout the light-producing InGaN layers—leading to the highest potential yield. For a flat wafer carrier, the wafer must be nominally flat throughout the MQW growth.

Use of the deflectometer in-situ metrology provides process engineers with the data to achieve a uniform wafer temperature during the MQW phase of the growth to optimize and maintain wafer yield.

CURVATURE AND YIELD

Understanding and controlling wafer curvature helps to minimize within-wafer wavelength range. Table 1 shows the estimated effect of wafer curvature on InGaN LED wavelength yield.

	Curavature Non-Ideality	Substrate, Sapphire	Production Stdev, nm	5nm yield wrt Scenario A
Scenario "A" optimal 2" curvature	0 km^{-1}	2"	2.89	0.0%
"A" + 10km^{-1}	10 km^{-1}	2"	3.07	-2.9%
"A" + 20km^{-1}	20km^{-1}	2"	3.24	-5.6%

Table 1: Estimated Effect of Wafer Curvature on InGaN LED Wavelength Yield

If it were possible to achieve near-perfect wafer flatness at MQW layering, wafer curvature on a 2-inch sapphire wafer would be essentially zero inverse kilometers (km^{-1}), (a standard measure of curvature). This results in a 2.89nm standard deviation of wavelengths distribution across the wafer, for close to 100% yield within a 5nm bin.

While this is only theoretical, it can be seen that even small changes in wafer curvature have a measurable impact on yield: a curvature of 10 km^{-1} translates into a loss of 2.9% of devices. As wafer sizes transition from 2" to 4", the potential losses become quite significant: a 4" wafer with the same 10 km^{-1} curvature results in a projected 10.6% loss of yield.

PROCESS PARAMETER EFFECTS ON SUBSTRATE CURVATURE

Figure 3 depicts the effect of growth process parameter changes on substrate curvature as measured by the DRT-210. The substrate in the first process run (black curve) exhibits a curvature of -50 km^{-1} (equivalent to approximately 15 microns concave bow) during the MQW growth layers, which is non-optimal for uniformity.

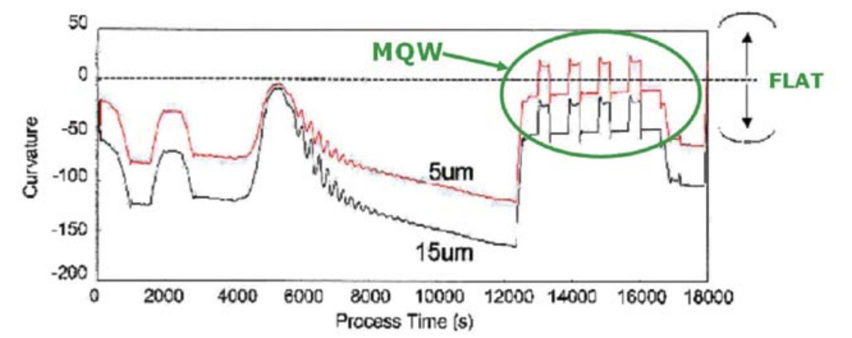


Figure 3. Characterization Example: Effect of Substrate Bow on LED Processes.

The in-situ measurement enables immediate process adjustments that are implemented during the next run. By adjusting either process temperature or GaN thickness, a different substrate pre-bow can be established before growing the MQW layers.

In this example the user adjusts the process temperature for the next run (red curve) which results in a much flatter wafer at MQW with a nominal bow of just 5 microns.

Figure 4 depicts a close-up view of the MQW for these processes and how in-situ deflectometry measures curvature accumulation during MQW growth with very high resolution.

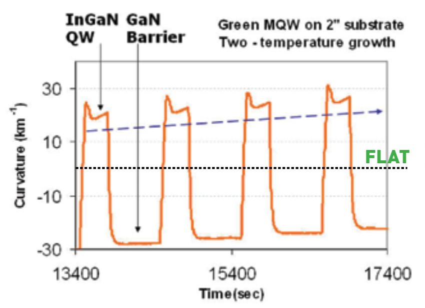


Figure 4. Characterization Example: Curvature Accumulation During MQW Growth

Four successive Quantum Well (QW) layers in a process for creating green HB-LEDs on 2" substrates are shown, exhibiting specific curvatures of the successive InGaN QW and the GaN barrier layers. Although achieving 100% flat uniformity during MQW growth is unlikely, it is possible to use the curvature information captured to refine processes to keep the curvature accumulation within tight tolerances.

NUCLEATION CASE STUDIES

Both Low Temperature (LT) GaN and Aluminum Nitride (AlN) can be used for nucleation on sapphire substrates. Since LT GaN nucleation is patent protected, MOCVD users may opt to utilize AlN nucleation; however, detailed understanding of GaN bulk growth on top of AlN nucleation layers remained unclear.

With GaN nucleation on sapphire as a basis for comparison, three separate experiments were conducted using in-situ deflectometry to evaluate how each individual process parameter affects substrate curvature and to gain further insight in the following areas of study:

- AlN nucleation on sapphire with varying nucleation temperatures
- Si-doped bulk GaN vs. Undoped bulk GaN growth on AlN nucleation
- MQW growth on Si-doped bulk GaN with GaN nucleated templates vs. AlN nucleated templates

Case study #1: This study evaluated the use of AlN buffer layer nucleation processes at different growth temperatures as compared to standard GaN nucleation.

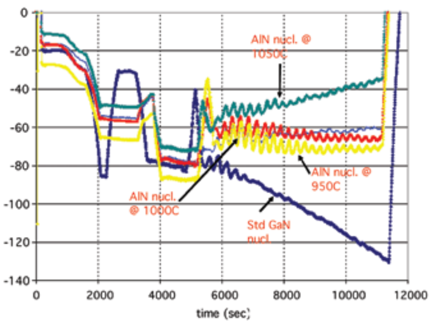


Figure 5. Curvature of GaN as function of nucleation layer temperature

In Figure 5 the substrate curvature during GaN bulk nucleation layer growth is depicted for multiple AlN nucleation runs at varying process temperature conditions ranging from 950ºC to 1050ºC.

It can be seen that variations in the AlN nucleation temperature result in substantial changes in substrate curvature when the bulk GaN growth is complete. AlN nucleation at 950ºC results in a concave substrate curvature of -70km^{-1} at the end of the bulk GaN growth while at 1050°C substrate curvature is -35km^{-1}. For comparison purposes substrate curvature after standard GaN nucleation is an even more concave -130 km^{-1}.

Case study #2: The impact to wafer substrate curvature of Si-doped bulk

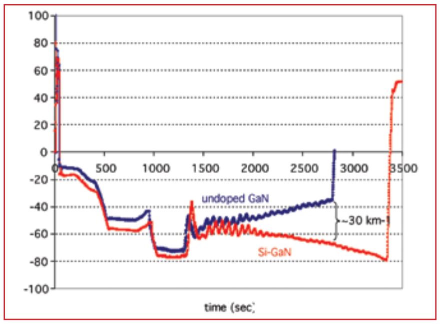


Figure 6. Undoped GaN vs Si-GaN on AlN nucleation (1050°C)

GaN growth vs. undoped bulk GaN growth is demonstrated in Figure 6. Bulk GaN growth in both cases occurred on top of AlN nucleation grown at 1050°C.

After an equivalent growth time period the influence of adding Si doping to the bulk GaN layers results in an increase in the wafer curvature by -30km.$^{-1}$ The figure also indicates that extending the bulk GaN growth time period permits the grower to further tailor the wafer curvature prior to MQW growth.

Case study #3: A comparison of MQW growth on top of Si-doped bulk GaN with GaN nucleated templates vs. AlN nucleated templates at 1050°C is shown in Figure 7.

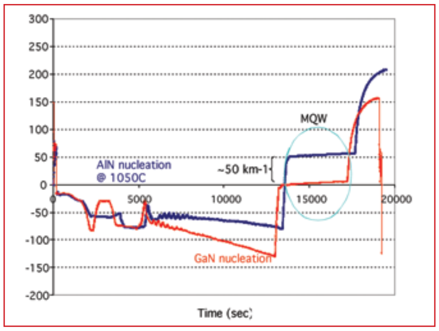


Figure 7: MQW growth on Si-GaN with different nucleation layers

AlN nucleation at 1050°C creates a wafer curvature of approximately -75 km^{-1} after bulk GaN growth. This pre-MQW bow results in a wafer curvature during the MQW layers that is highly convex. In this instance the approximately +50 km^{-1} curvature could lead to a drastic reduction in device yields due to wafer non-uniformity.

With GaN nucleation, it can be seen that a more concave wafer curvature of approximately -135 km^{-1} resulted from the experiment and lead to a nearly flat +5km^{-1} wafer curvature during MQW growth.

These three case studies demonstrate that both AlN and GaN nucleation have effects on wafer bow at MQW, that wafer bow can be influenced by both the growth temperature of the AlN nucleation layer and the introduction of Si-doping in bulk GaN layers.

These relationships, and the ensuing modifications to GaN and AlN nucleation processes, could not have been readily characterized without the use of in-situ temperature and wafer deflection metrology.

With use of deflectometry the MOCVD grower can measure and evaluate substrate curvature and then adjust process conditions for immediate impact to the wafer run yields.

CONCLUSION

In-situ metrology using the Veeco TurboDisc DRT-210 In-Situ Process Monitor provides real-time insight into the MOCVD epitaxial growth processes. Using the DRT-210 saves time when making changes to growth processes and enables better understanding of production variations.

By creating a single integrated in-situ metrology platform with excellent dataset visualization features, Veeco significantly enhances the value and performance of the TurboDisc® K-Series GaN MOCVD platform for HB-LED manufacturing, increasing process growth uniformity and device yield potential.

The unique combination of deflectometer, reflectometer and thermometer enables MOCVD process engineers to:

- Fine-tune within-wafer uniformity by detailing wafer curvature during epitaxial growth
- Help monitor wafer reflectivity to understand and better control nucleation and epi-roughness
- Provide accurate temperatures of wafer surface for opaque substrates and wafer pocket for transparent substrates
- Deliver highly reliable and repeatable results in real time, so process uniformity can be optimized faster

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