Connected Metrology® – Optical wafer characterization along the semiconductor manufacturing chain

In the domain of semiconductor device manufacturing, the demand for uniformity, precision, and process transparency is continuously increasing. This white paper details how LayTec's Connected Metrology® serves as a strategic enabler for new application domains by combining in-situ and ex-situ monitoring tools across all critical production stages – enabling predictive control, real-time feedback, and wafer-level optimization. Using the example of Vertical-Cavity Surface-Emitting Lasers (VCSELs) for space applications, the strategy, tools, and results achieved through Connected Metrology® are presented.

A prominent example where Connected Metrology® demonstrates its value is in the production of VCSELs for quantum-based rotation sensors and satellite communication modules. In such space-bound applications, tiny deviations in stop-band center or Fabry-Pérot dip positions can shift the cavity resonance outside tolerance, rendering devices unusable. By combining in-situ epi monitoring, wafer-specific feed-forward control, post-epi spectral fitting, and in-situ etch end-pointing, manufacturers can achieve the level of reproducibility and robustness required for next-generation space photonics.

From substrate to systems: The Connected Metrology®

LayTec's concept of Connected Metrology® spans the full front-end compound semiconductor manufacturing chain – from epitaxial growth to device production. Each stage integrates optical measurement tools that enable tight control of physical parameters and feed valuable data downstream.

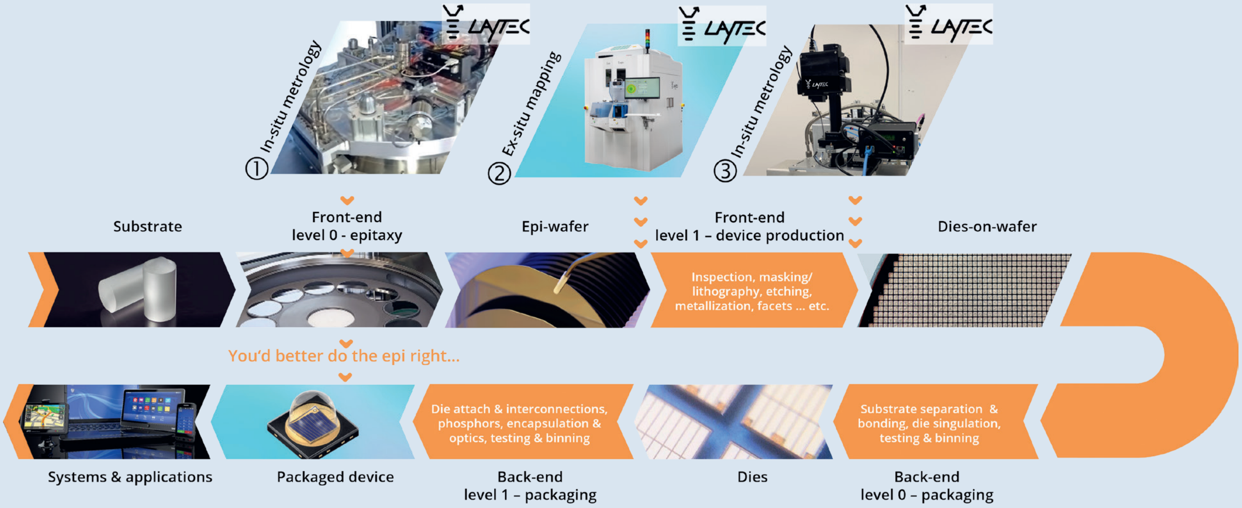

Figure 1: The full Connected Metrology® workflow across the semiconductor manufacturing chain. In-situ metrology is applied during epitaxy and etching, while ex-situ mapping characterizes epi-wafers before further processing. This enables predictive control of device performance throughout the chain – from substrate to final systems and applications.

In the following, we illustrate how each stage of the Connected Metrology® chain contributes to robust VCSEL production – from early growth monitoring, through calibration and uniformity control, to final precision etching.

Real-time in-situ monitoring during epitaxy: LayTec's EpiCurve® TT InspiRe

During epitaxial growth, LayTec's EpiCurve® TT measures wafer curvature, emissivity-corrected temperature, and multi-wavelength reflectance, providing temperature accuracy better than ±1 K, growth rate measurement up to 1% accurate, and curvature precision of ±0.5 km^{-1}. With the spectral extension InspiRe a comprehensive spectral "fingerprint" of the growth process is recorded, showing the optical evolution of each layer in real time.

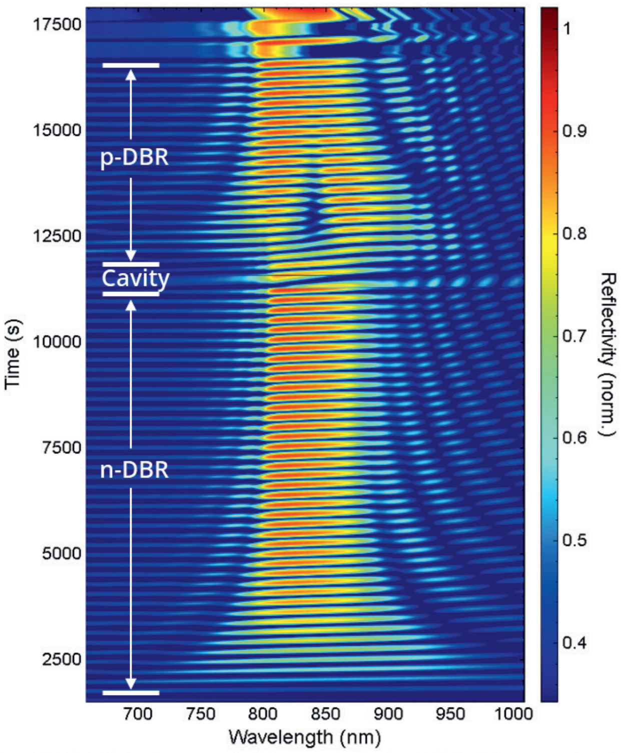

Figure 2: In-situ reflectance data captured over the course of a VCSEL growth. The clear separation of p-DBR, cavity, and n-DBR layers illustrates how Fabry-Pérot oscillations serve as real-time markers of layer thickness and refractive index contrast.

This fingerprint not only reveals layer transitions but allows direct monitoring of growth dynamics – offering valuable insight into process stability, uniformity, and potential deviation early in the manufacturing sequence.

In-situ assisted feed-forward control for wafer uniformity

One of the most critical innovations enabled by EpiCurve® TT InspiRe is in-situ assisted feed-forward control. This approach leverages the optical fingerprint obtained during growth to automatically intervene in the continuing growth process. Reflectance and curvature data are not just archived – they are used to calculate growth rate deviations and perform adjustments in real time. Feed-forward boosts yield, reduces scrap, and shortens recipe tuning – an innovation still rare in most fabs.

For VCSEL structures, maintaining precise spectral positions of the stop-band center (SBC) and Fabry-Pérot (FP) dips is essential. The system enables wafer-by-wafer parameter tracking, identifying outliers and refining pocket-specific recipe parameters to improve overall run uniformity.

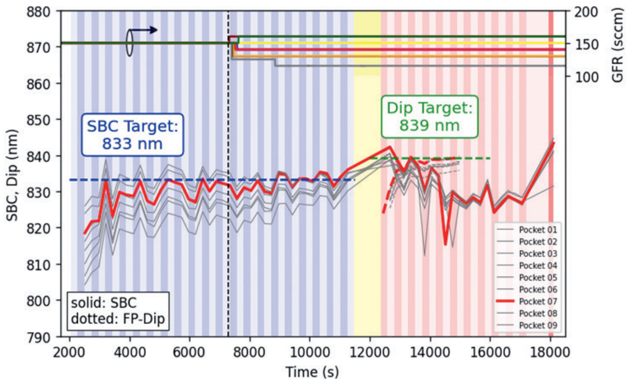

Figure 3: Time-resolved tracking of SBC and dip targets across multiple wafers (or pockets) during a production run. Colored zones mark recipe steps. The data supports real-time adjustments to maintain tight spectral uniformity across wafers.

This approach leads to high reproducibility and consistency in complex structures, while also enabling insights into growth rate drift and reactor-specific dynamics.

Spectral fitting and post-epi analysis

Following epitaxy, LayTec's EpiX® C2C system performs ex-situ, automated cassette-to-cassette white light reflectance (WLR) and photoluminescence (PL) wafer mapping with high spatial and spectral resolution. Post-epi results feed directly into growth corrections and TRIton® models, making EpiX® the key link in Connected Metrology®.

In addition to the system's capability of evaluating stopband and cavity-dip properties, spectral fitting techniques are used to further derive key parameters such as layer thicknesses and compositions. To that end, wafer-specific analysis results from in-situ monitoring during epi such as layer thicknesses are directly imported and used as starting values. In practice, the system can rapidly validate growth accuracy, identify delta deviations, and tune layer thicknesses for subsequent growth runs by comparing measured spectra against simulated ones. The wafer mapping results are then fed back to the epi process for run-2-run control to continuously keep the epi in spec.

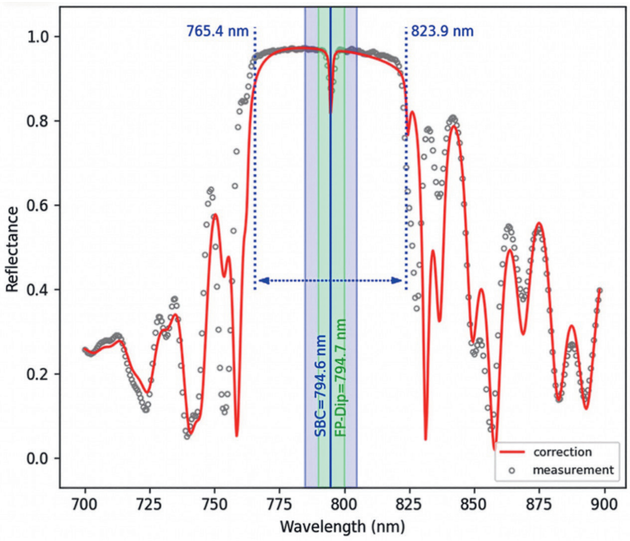

Figure 4: Reflectance curve of a VCSEL cavity structure showing raw measurement (gray points) and fitted model (red curve). Key spectral features such as SBC and FP-Dip positions are precisely extracted to quantify device performance.

EpiX® is not only valuable for process control in production but also ideally suited for calibration campaigns. These measurements are essential for post-epi calibration and production tuning. They allow engineers to quantify how well the actual structure matches the design and to identify causes of deviation.

In-situ metrology during plasma etching: LayTec's TRIton®

As semiconductor devices evolve in complexity and stack height, epi wafers have become even more valuable. To maintain this value, precision during plasma etching is just as critical as during epitaxial growth. One of the most challenging steps in VCSEL production is etching through multiple optical layers without compromising the device structure. This requires accurate, layer-specific endpoint detection (EPD), which is where LayTec's TRIton® system plays a pivotal role.

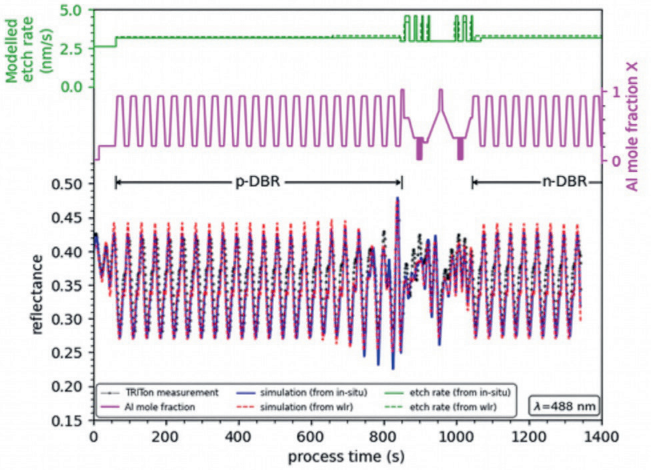

Figure 5: Measured etch transient VCSEL structure (black points) compared to expected transients calculated from layer stacks derived from in-situ epi (blue) and post-epi (red) measurements using EpiCurve® TT InspiRe and EpiX®, respectively.

TRIton® leverages multi-wavelength UV-VIS-NIR reflectometry to monitor the etching process in real time. Crucially, TRIton®'s real-time monitoring is backed by model-based analysis. Its unique strength lies in its ability to precisely track the remaining thickness of all layers during etching by comparing the measured etch transient to an expected etch transient. This expected transient is calculated from the wafer-specific layer structure obtained in earlier process steps, i.e. during epitaxy from EpiCurve® TT InspiRe measurements refined by post-epi analysis using EpiX®. Just using the nominal stack, however, would not be sufficient. Unlike conventional endpoint methods, TRIton® doesn't merely react to a signal drop but understands where in the stack the etching currently is, enabling EPD at virtually any point in the layer stack, not just at or after dedicated interfaces and making plasma etching a predictable, controllable step rather than a source of yield loss.

This step – in-situ etching control – completes the feedback loop of Connected Metrology®, adding a final layer of precision before the wafer transitions into back-end processes like singulation and packaging.

For more information, reach out to **info@laytec.de** or visit **www.laytec.de**.

Conclusion: metrology as a strategic enabler

With increasing complexity in semiconductor device architectures, the need for connected, adaptive, and high-precision metrology is more urgent than ever. LayTec's Connected Metrology® platform addresses this need by embedding knowledge-driven tools into every critical step of the front-end production line.

Connected
Metrology®

From real-time growth monitoring and feed-forward control to ex-situ mapping and spectral fitting, the data generated enables more than quality control – it enables intelligent, predictive manufacturing.

Looking ahead, the principles of Connected Metrology® are equally applicable to existing or emerging device classes such as edge-emitting lasers, photonic integrated circuits, and quantum devices–opening the path toward a new level of industrial process control in compound semiconductors.

About us

LayTec, founded 1999 in Berlin, is a major provider of in-situ and in-line optical metrology for thin-film processes.

These metrology tools are used in a broad range of thin-film applications such as LED & laser production, power devices and transistors, thin-film photovoltaics, oxide and organic deposition as well as other large area deposition processes. LayTec's integrated metrology provides access to all key thin-film parameters in real-time – either in-situ, during the deposition process, or in-line. Also, in-situ metrology tools for dry etching have been added expanding LayTec's portfolio along the production chain.

Beyond these integrated methods, LayTec also offers mapping solutions which ideally complement in-situ measurements by providing uniformity analysis of the deposited layers. The implementation of LayTec metrology systems in production processes significantly shortens development cycles and enables an efficient quality control that helps to considerably reduce production and development costs.