Eliminating bowing in blue LED and laser epi

LayTec and Ferdinand-Braun-Institut describe new in-situ technology for optimizing the growth of blue LEDs and laser diodes by reducing wafer bowing during epitaxial growth.

A new in-situ sensor from LayTec that provides simultaneous in-situ strain, temperature and reflectance measurements is helping blue LED and laser development and production. The sensor is being applied successfully to optimize MOCVD growth of GaN-based devices at research institutes and industrial companies worldwide. Recent results at Ferdinand-Braun-Institut in Berlin, Germany illustrate the method's effectiveness.

MOCVD growth of GaN-based LED and laser structures

Metalorganic chemical vapor deposition (MOCVD) is the most important method for manufacturing nitride-based microelectronic and optoelectronic devices. If the high-brightness white LED is going to replace the incandescent light bulb, then its price per lumen of light output must fall substantially. To achieve this goal, better understanding of the GaN growth process and improvements in the reproducibility are essential. Furthermore, high-volume LED production needs efficient multiwafer growth equipment with reliable in-situ process control. One major task for LED manufacturers worldwide is process yield optimization. In this regard, the improvement of wavelength homogeneity across the wafer diameter is of crucial importance.

For blue and white LEDs, thin (Al,In,Ga)N films are grown on foreign substrate materials such as sapphire or silicon carbide, because GaN substrates are still expensive and scarce. Due to the lattice mismatch and different thermal expansion coefficients between the substrate and the epitaxial film, strong stresses evolve during III-Nitride growth and cause the wafer to bend on a macroscopic scale.

An important impact of wafer bowing during growth is the change in thermal contact between the wafer and the substrate holder. This is especially important for indium-containing compounds, since In incorporation during MOCVD is known to be very temperature sensitive [1]. This implies that bowing during growth will cause inhomogeneities in the active layers (quantum wells) of the device.

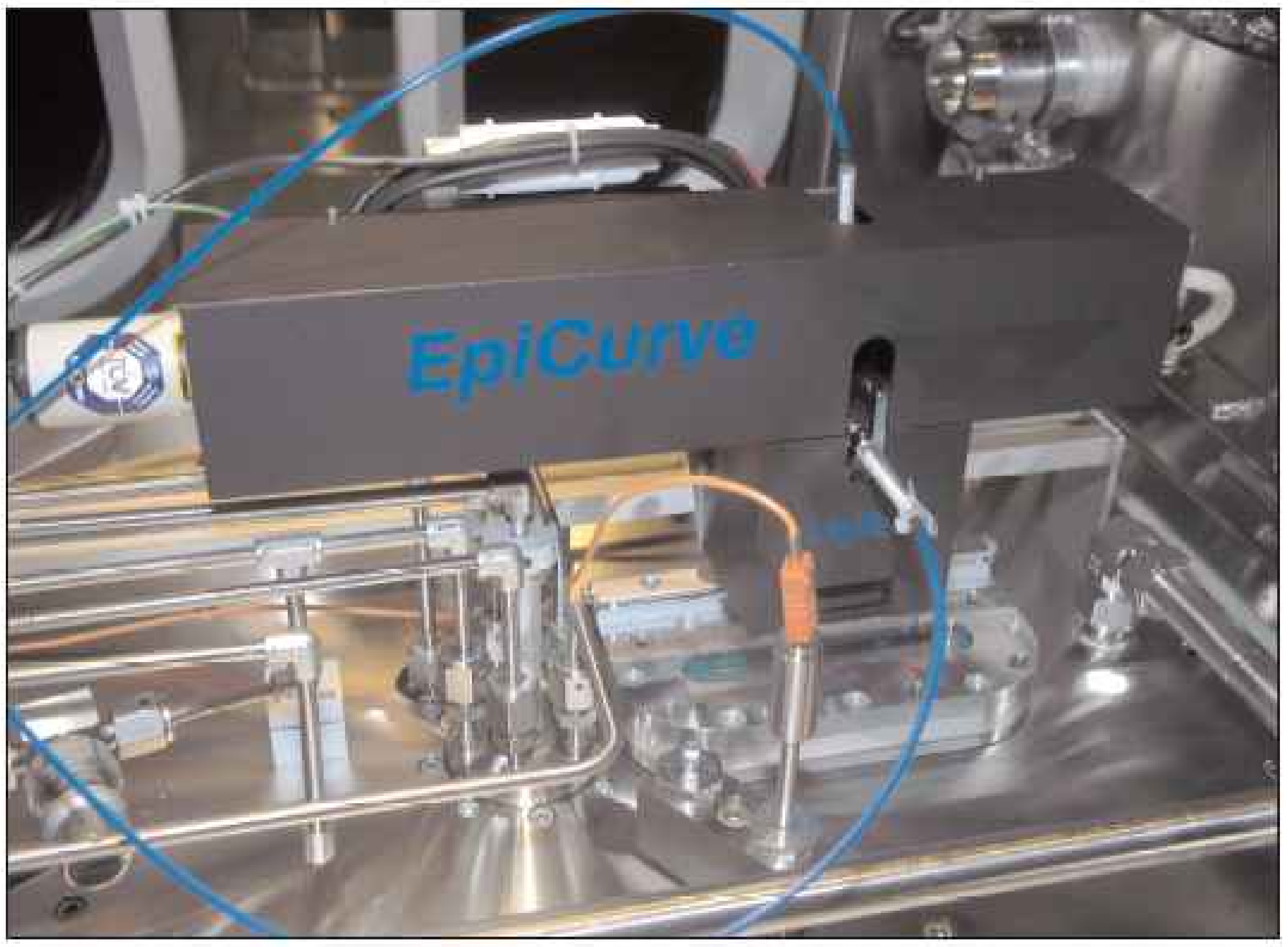

Figure 1. A production-scale MOCVD reactor at FBH, equipped with an EpiCurve TT curvature sensor for the determination of strain, temperature and growth rate during GaN deposition.

Therefore, to understand and optimize the growth process, it is essential to monitor in-situ how lattice mismatch and differences in thermal expansion coefficient contribute to the total stress at growth temperatures.

To enhance this understanding, LayTec has developed EpiCurve TT — a sensor that provides curvature measurements, emissivity-corrected pyrometry for wafer temperature measurements, and reflectance at two wavelengths (see Figure 1). The curvature sensor has a bowing resolution of $\delta(1/R_c) = \pm\ 1\text{km}^{-1}$ (where R_c is the radius of curvature). The relevant basic experimental set-up has been published in [2]. The MOCVD system has to be equipped with a standard optical viewport for normal incidence access.

Accurate wafer-selective susceptor surface temperature (T_{wafer}) measurements, in parallel with the bowing measurements, are necessary to gain deeper insight into the growth process. T_{wafer} is the most important parameter in MOCVD, as it determines both the gas-phase decomposition and the surface processes. The susceptor surface temperature immediately under the wafer often differs from the process temperature measured at the susceptor back-side, since the gas-foil rotation of the satellites or cold process gases tend to cool the front side of the substrate holder. Therefore wafer-to-wafer and run-to-run reproducibility of T_{wafer} have to be checked carefully.

The integrated reflectance measurement at 405nm and 950nm gives access to the growth rate, composition and surface morphology during growth, and for each wafer separately. Again, statistical process control (wafer-to-wafer as well as run-to-run) can be applied to verify the reproducibility in a production-line multiwafer MOCVD system. The 405nm signal is ideally suited to monitor InGaN quantum wells, as at this wavelength the GaN layers are absorbing.

How to eliminate the bowing

The active region of devices emitting in the blue and green spectral range typically consists of InGaN multiple quantum wells (MQW). Reducing wafer curvature at the InGaN growth temperature should directly improve the composition uniformity and yield of optoelectronic devices. The Ferdinand-Braun-Institute has therefore conducted studies of how to design the process to reduce the wafer curvature at critical growth steps [3]. The dependence of wafer bowing on substrate properties, growth temperature and the insertion of strain-compensating interlayers was carefully examined to improve the uniformity of light emission.

Figure 2 shows the wafer curvature (lower graph) and reflectance at 950nm and 405nm as well as the emissivity-corrected wafer temperature (upper graph) during growth of a GaN-based laser diode test structure. As can be seen, already the initial curvature of sapphire wafers from different batches varies by about 20km^{-1}. This difference in $1/R_c$ is sustained during the whole growth process and has an impact on wafer-to-wafer reproducibility. Here, multiple wafer in-situ measurement substantially reduces the effort of pre-characterization of substrates from different batches.

During the high-temperature desorption step prior to growth, the sapphire substrate has a concave bow due to the temperature gradient between the wafer backside (heated by the hot wafer carrier) and the wafer topside (cooled by the process gases and radiation towards the cold reactor top). SiC substrates (not shown here) behave differently to sapphire wafers: according to their much better thermal conductivity, no thermal-induced concave curvature is observed during heating.

While low-temperature GaN nucleation on sapphire leads to a slight convex wafer bowing, the following high-temperature growth of GaN layers is characterized by increasing concave wafer curvature (Figure 2). The origin of this tensile stress during high-temperature GaN growth can be assigned to the process of coalescence of the nucleation layer islands. For example, the number and size of GaN grains during nucleation is known to affect the magnitude of tensile stress during GaN growth. Additional tensile stress is generated by adding Al to the compound, since AlN has a smaller lattice constant than GaN. Accordingly, during growth of the cladding layer (Figure 2: AlGaN/GaN superlattice) the change in curvature shows a larger slope compared to the GaN buffer.

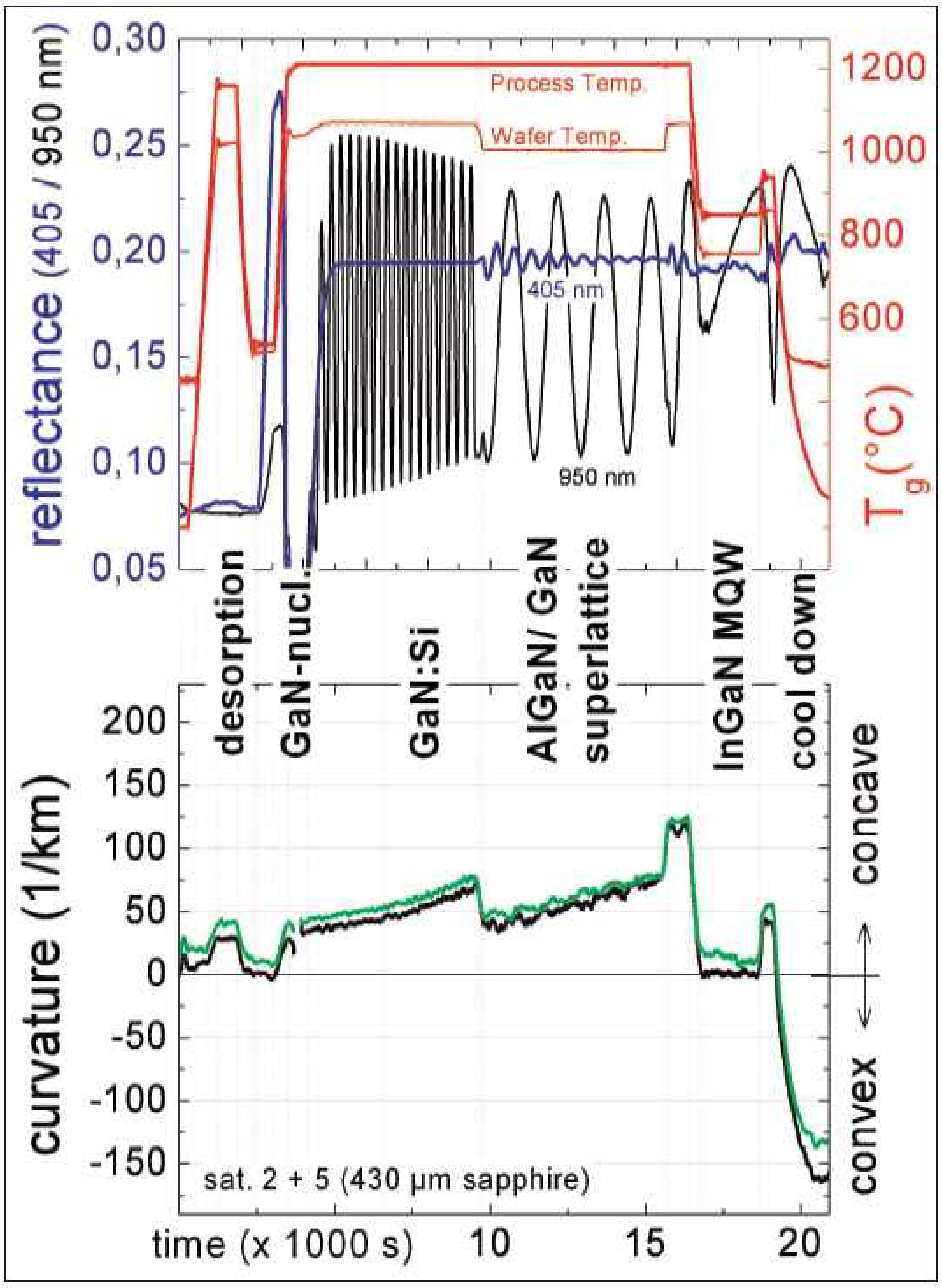

Figure 2. In-situ measurement of reflectance and surface temperature (upper graph) as well as wafer curvature (lower graph) during growth of a GaN-based laser test structure.

As the temperature varies, the bowing changes due to the different thermal expansion coefficients of the epitaxial layers and the substrate beneath. For example, when cooling down from the growth temperature, the GaN layer becomes convex, since the thermal expansion coefficient of GaN is smaller than that of sapphire. Since a different bowing rate with cooling for different substrate thicknesses can be observed, the temperature of zero bowing also depends on the substrate thickness.

For the growth of the light-emitting active layer, the wafer should be as flat as possible. Otherwise, temperature inhomogeneities across the wafer during InGaN growth lead to inhomogeneities in the emission wavelength of the final device. This can be achieved by selecting an appropriate substrate thickness and by optimizing the growth temperature. However, the growth temperature is a very restricted parameter to

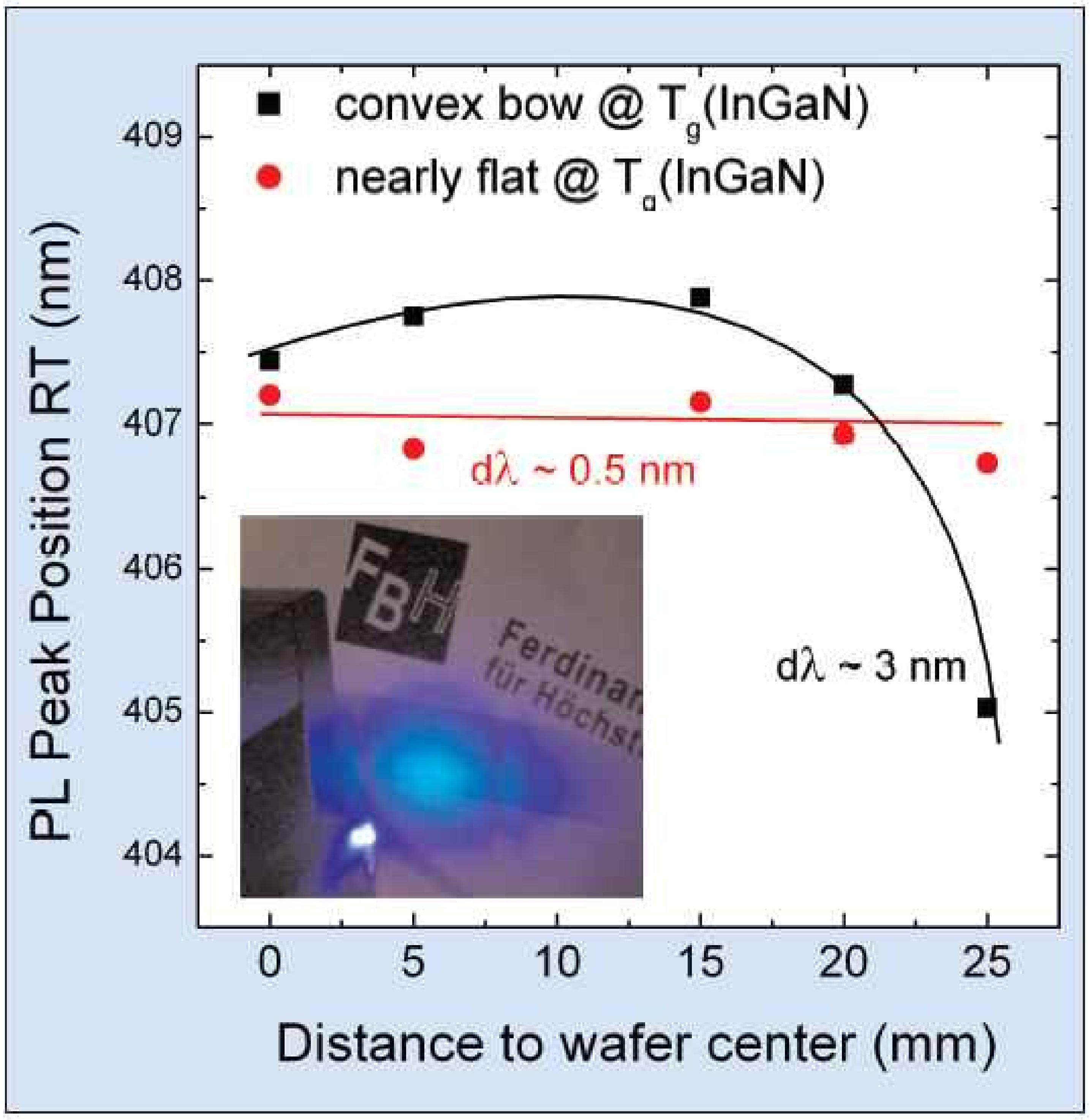

Figure 3. Uniformity of room-temperature PL peak position, comparing wafer with high and low convex bow at InGaN growth temperature. The inset shows 400nm light emission from an optically pumped laser structure.

adjust for flat wafer growth conditions, since the material quality and composition in the InGaN active layer are strongly affected.

As a consequence, further ways of controlling the bow by introducing compressive stress are desirable. Solutions for engineering the built-in stress in GaN include low-temperature (Al,Ga)N interlayers with an Al concentration above 60% and InGaN compliance layers. While AlGaN with such high Al content and AlN suffer from having insulating properties, n-type doping of InGaN can easily be achieved, offering vertical current transport in the optoelectronic device structure. For example, the insertion of a 100nm-thick Si-doped $In_{0.06}Ga_{0.94}N$ layer within a GaN/AlGaN heterostructure introduces convex curvature of about $20km^{-1}$ [3].

Figure 2 shows an example of reduced wafer bow during growth of the active layer in a laser diode structure: The wafer in pocket 2 (black line) is nearly flat at the InGaN growth temperature. Accordingly, ex-situ characterization with room-temperature photoluminescence (PL) demonstrates the impact on device properties. Figure 3 displays the variation of the peak wavelength over the 2-inch wafer radius for substrates exhibiting either a high or low convex bow at the InGaN growth temperature. In contrast to the emission non-uniformity of about 3nm in the case of unoptimized growth, flat wafer conditions result in very good wavelength homogeneity (~0.5nm).

Summary

The unique combination of curvature measurements with temperature and reflectance monitoring makes EpiCurve TT a technological breakthrough in developing and manufacturing high quality crack-free wafers. The real-time access to wafer bowing enhances growth uniformity and yield, which finally leads to greater efficiency in R&D and an immense reduction in time and costs for production facilities. In the future, a quantitative analysis of wafer bowing throughout the full epitaxial process retracing the lattice constant mismatch between the substrate and every single layer of the growing structure will be possible. Apart from MOVPE, the sensor is applicable to MBE and HVPE reactors.

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