Information Note

LayTec in-situ sensors

Wafer Curvature Measurements for Real-time Optical Control of Epitaxial Growth

During hetero-epitaxial growth, when the lattice constant of the growing film differs from the substrate's lattice constant, the wafer surface bows, no matter whether the lattice mismatch is intended or not. As the growth on large scale wafers increases, bowing effects are becoming of a larger importance. Yet the newly developed high-resolution real-time curvature sensors provide direct access to these characteristics and in some cases even enable in-situ determination of the actual thin-film composition. Moreover, wafer bow has a direct impact on the yield in modern mass-production compound semiconductor industries. This information note is a basic introduction into the principles of curvature measurement to help you understand and analyse wafer bow measurements in MOCVD and MBE processes.

1. Basic principles

The principle of measurement is explained visually in Fig.1: two parallel laser beams are directed to the wafer. The initial distance between the beams is Δxo. In the case of a perfectly flat wafer (Fig.1a) the distance between the reflected beams remains the same (ΔxD=Δxo), as can be detected by a respective linear detector array. If the wafer is not flat, the detected distance ΔxD between the two reflected beams differs from the initial distance Δxo. In the case of a concave bow (Fig. 1b), which can be defined by a positive radius of curvature RC>0, the distance decreases, whereas a convex bow (Fig. 1c) defined by a negative radius of curvature RC<0, makes the distance larger.

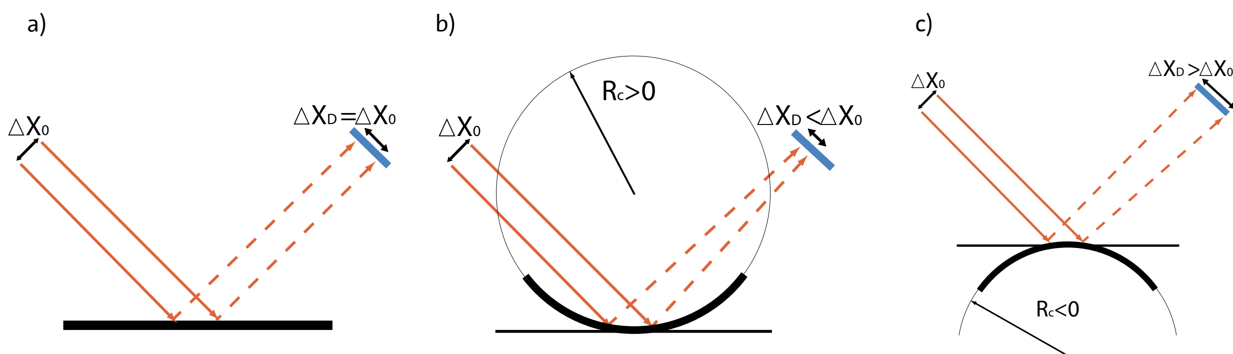

Fig. 1: Principle of wafer bow measurement: a) flat wafer, b) concave wafer bow and c) convex wafer bow

In compound semiconductor epitaxy wafer bowing is normally small (R > 2 m). Hence, a simple linear relationship between the measured distance of laser spots at the detector Δx_D and the bowing radius R_C can be applied:

$$C = \frac{1}{R_C} \cong \frac{\Delta X_D - \Delta x_o}{2\Delta x_o Z_D} \equiv \frac{S}{2\Delta x_o Z_D} \qquad (1)$$

Z_D is the distance between wafer and detector. S is the raw signal, i.e. the magnitude of change in the laser spot distance by wafer bow with respect to a perfectly flat wafer. With C we define the pa-

rameter "curvature" calculated as the inverse of the bowing radius R_C. We use C instead of R_C because in this case we have a curvature of zero for a perfectly flat wafer instead of dealing with a (mathematically correct) infinitely large bowing radius of $R_C=\infty$. The curvature C is measured in units of [km^{-1}] because the detected curvature in compound semiconductor technology is typically very small and, hence, the related radius of curvature is large (in the order of $kilometers^{-1}$).

The sensitivity of the method increases when the initial distance Δx_o is larger (see Fig. 2). However, if the initial distance is too large, the size of the detector might be too small to detect both beams throughout the whole measurement. The range of curvature detectable is therefore limited by Δx_o and decreases with increasing Δx_o.

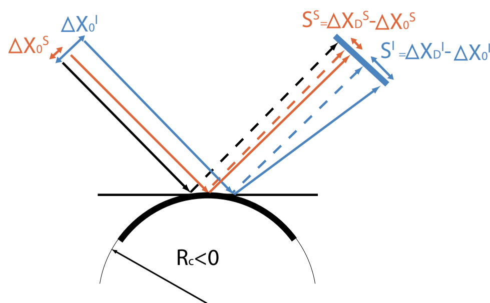

Fig. 2: A larger distance between the initial beams makes the measurement more sensitive to smaller changes in the total bow.

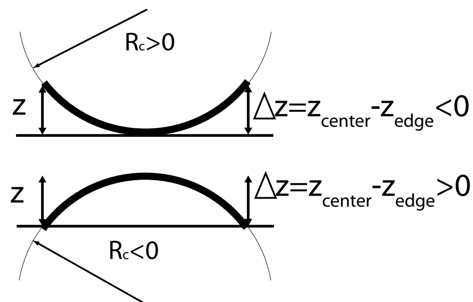

Fig. 3: Definition of wafer bow Δz: Δz gives the maximum distance between the actual bow and the wafer holder (susceptor).

The final parameter to be defined here is the wafer bow (Fig. 3): the wafer bow Δz describes the maximum distance (measured in microns) between the wafer holder (typically perfectly flat) and the bowed wafer. d is the diameter of the wafer. The total bow scales with the diameter of the wafers!

$$\Delta z = R_C - \sqrt{R_C^2 - \left(\frac{d}{2}\right)^2} \qquad (2)$$

This parameter is of high importance especially in processes where the wafer holder (susceptor) determines wafer temperature by direct contact heating. Therefore, the absolute value of wafer bow $|\Delta z|$ usually has a direct impact on temperature uniformity across the wafer and, hence, on the yield of the process.

2. The real measurement: facts to be considered

In real epitaxial growth systems a number of specific situations have to be considered:

- The wafers move, rotate and often wobble. So, the wafer rotation and the curvature measurement have to be synchronized with high precision.
- The view-port in gas-phase systems is very small to minimize negative effects on laminar gas flow. Hence, the sensitivity of bow measurement cannot be enhanced simply by widening the initial distance between laser beams.

- Sometimes wafers show a radial bowing variation. In this case, accurate measurement can be guaranteed only if the beams are reflected exactly around the center of the wafers.
- The distance between the wafers and the detector may slightly change depending on the reactor temperature. Accurate calibration is therefore needed at both, room temperature (where the wafers are loaded) and the growth temperature.

LayTec has developed and optimized curvature optical heads that solve these problems in a variety of MOCVD and MBE systems, so that the user can focus on the curvature measurement.

3. Four major effects contributing to the wafer bow during epitaxial growth:

a) The specifics of the wafer polishing technology causes an initial bow of the wafer, which can be seen already after loading the bare substrate and gives a bow offset, which remains constant throughout the growth process.

b) For MOCVD, a vertical temperature gradient is typical (cold-wall reactors): the back-side of the wafer is heated by the susceptor directly, whereas the top-side faces the 'cold wall' (shower head, ceiling) and is cooled due to the heat-transfer from the wafer surface to the cooled wall. The vertical temperature difference between wafer surface and back-side is rather small (~1...3K), but its contribution to wafer bow is usually considerable. The curvature changes with gas concentration and gas flow as Fig. 4 shows. Low ohmic substrates are less effected than high-omic ones due to their good thermal conductivity.

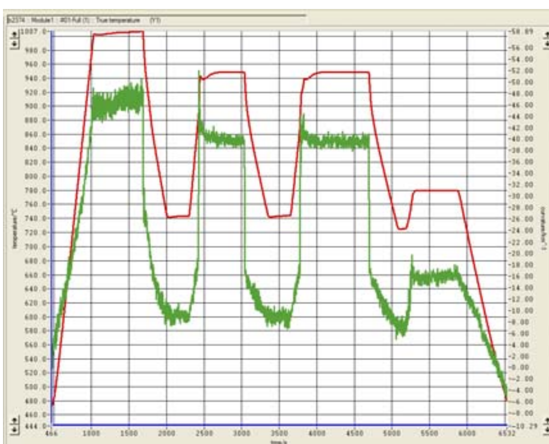

Fig. 4: Curvature response (green) of a bare sapphire substrate in an AIX200/4RF-S reactor subjected to temperature changes (red) and total pressure changes (arrows) as typical for an LED process (here, however, without performing any growth!): the curvature of the bare sapphire substrate is following gradually the back-side heating but additionally shows steep rises and falls whenever the surface cooling changes abruptly with total pressure (as indicated by the arrows).

Fig. 5: Change of the bow (green) of GaN on sapphire when the temperature (red) changes from 1075°C to 400°C: every change in the absolute temperature of the wafer causes significant changes in wafer curvature due to the different linear expansion coefficients between the substrate and the films.

c) After layers have been grown on the substrate, every change in the absolute temperature of the wafer causes significant changes in wafer curvature due to the different linear expansion coefficients between the substrate and the films. Fig. 5 demonstrates these changes of the bow for GaN / Sapphire when the temperature changes from 1075°C to 400°C.

d) During growth of films under constant conditions (constant temperature is of the highest importance!) the curvature changes linearly in all non-lattice-matched (to the substrate) growth conditions. In Fig. 6 the growth rate of the film r_f is measured time by analysing in-situ reflectance data at the same with the curvature measurements. The slope of curvature can be used to calculate lattice mismatch directly according to the well-known Stoney's equation (3):

$$\frac{\Delta C}{\Delta t} = -\frac{6M_f}{h_s^2 M_s} \cdot r_f \cdot \frac{a_f(T) - a_s(T)}{a_s(T)} \qquad (3)$$

This effect can be used for a composition analysis (see Chapter 4 below).

All the four effects (a-d) contribute to the total wafer bow at a certain growth step of a compound semiconductor device structure. In consequence, their superposition should be analyzed alongside with systematical optimization of growth recipes for best lateral wafer temperature uniformity (zero wafer-bow) in critical growth steps.

4. Quantitative analysis of curvature measurements

For quantitative analysis, however, we can focus on the last effect (d) only, because it is the slope and not the absolute magnitude of curvature that has to be used. Fig. 6 provides an example of AlGaN and InGaN composition measurement applying Eq. (3) to real-time curvature data [1]: With increasing Al(In) content of AlGaN or InGaN ternary alloys, the lattice mismatch between the GaN buffer and the ternary alloy film increases - and so does the slope of bsolute value of curvature. The positive respectively negative sign of slope relates to the smaller or larger lattice constant of AlGaN or InGaN with respect to GaN. A quantitative analysis of the slope can therefore be used to determine the alloy composition already On-situ. Paper [1] by Brunner et al. is recommended for further reading. In 2005 LayTec has successfully released its curvature sensor **EpiCurve® TT** – the first sensor world-wide that measures wafer bowing, true temperature and reflectance simultaneously! It allows accurate strain monitoring, precise wafer temperature and growth rate analysis already during growth.

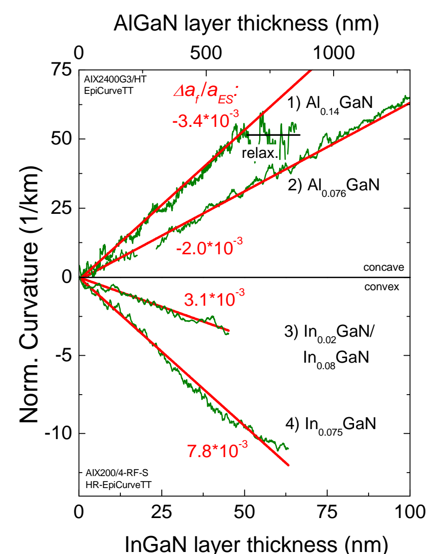

Fig. 6: AlGaN and InGaN composition measurement applying Eq. (3) to real-time curvature data.

[1] F. Brunner, A. Knauer, T. Schenk, M. Weyers and J.-T. Zettler, **Quantitative analysis of in-situ wafer bowing measurements for III-nitride growth on sapphire**; submitted to J. of Cryst. Growth.