In-situ metrology for CPV

An in-spec device performance requires homogenous properties of all layers in the device structures, such as layer thickness, ternary or quaternary composition, doping as well as interface and surface morphology. In the last ten years, in-situ metrology has opened the door to a tight fab-wide monitoring of all these parameters. This article describes the application of LayTec's in-situ metrology tools for development and production of concentrator photovoltaic cells (CPV).

1. Research and Development

At the Ioffe Physical Technical Institute (Ioffe PTI) in St. Petersburg, Russia, LayTec's EpiRAS® TT system is used for monitoring of multi-junction solar cell heterostructures based on III-V and Ge semiconductors (RAS=Reflectance Anisotropy Spectroscopy). One of the technological challenges is the growth of low defect III-V semiconductor structures on co-valent group IV Ge substrates. Here, EpiRAS® TT helps to control key growth parameters of the heterostructures throughout MOCVD process. The metrology system enables avoiding initial antiphase boundary formation at the III-V of Ge interface and provides wide-range spectral reflection measurements to determine ternary composition and growth rate, RAS signal to measure the doping level and, last but not least, the emissivity corrected pyrometry for an accurate temperature monitoring.

Fig. 1 demonstrates measurements made by EpiRAS® TT during growth of a triple-junction solar cell structure. In this run, the team at Ioffe used reflectance transient at 2.1 eV (Fig. 1a, red) for growth rate measurements. Yet the amplitude of the Fabry-Perot-Oscillations also provides information on the refractive index – a material parameter that directly correlates with the ternary composition of the III-V material. So, with the help of the EpiRAS® TT software database and appropriate fitting algorithms, the reflectance signatures even of very thin tunnel junction (TJ) layers can be translated into a composition value in real time.

Furthermore, the short wavelength reflectance anisotropy (RA) can be used for doping level determination. The team at Ioffe PTI correlated the RA signal at 3.8 eV (Fig. 1a – blue and 1b) with the doping values measured ex-situ and thereby established its own process control database. This helps to estimate the changes in doping on homo-interfaces already during device growth.

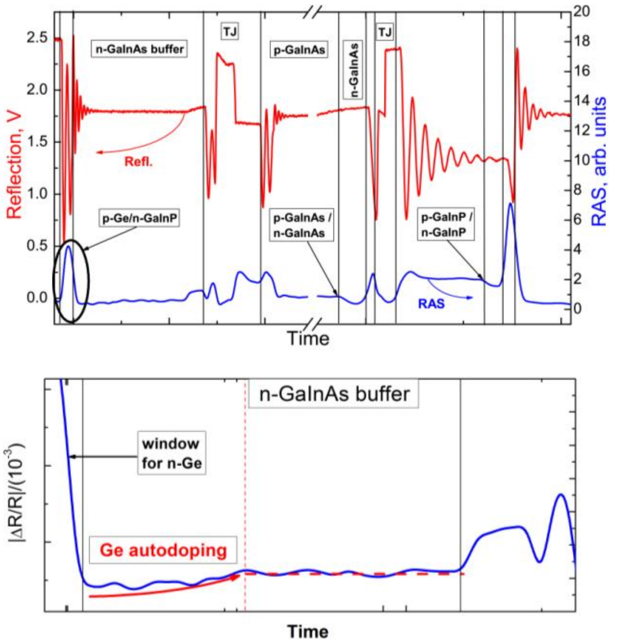

Fig. 1: complete growth of a triple-junction GaInP/GaInAs/Ge solar cell structure monitored by EpiRAS® TT at Ioffe PTI.

Fig. 1a: red - reflectance transient at 2.1eV, blue - RA measurement at 3.8eV. The reflectance signal is used for growth rate and ternary composition determination.

Fig. 1b: n-GaInAs buffer growth: blue – RA signal at 3.8eV helps estimate the doping concentration already during growth.

The most impressive results were achieved by analyzing the dependence of the RA signal just after the Ge/III-V interface formation. It has been found out that a high RA signal at the interface directly correlates with a rough interface and that Ge anti-doping directly shows up in the initial RA signatures. Researchers at Ioffe thereby optimized the growth conditions for window layers and buffer GaInP layers on Ge substrates and could determine the quality of the interface already during growth (Fig. 2 – red).

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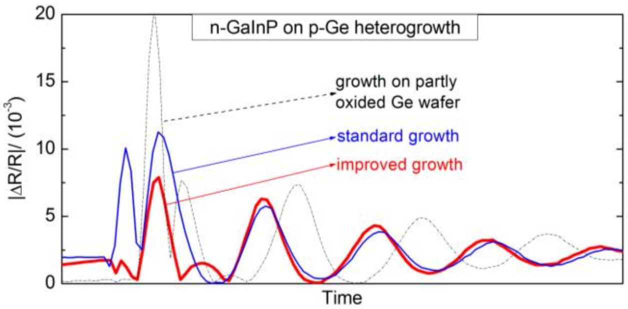

Fig. 2: n-GaInP on p-Ge heterogrowth. RA signal at 3.8eV: blue –standard growth, red – improved growth. The quality of the interface can be determined already during growth.

2. Industrial Production

This in-depth analysis of the in-situ data is well suited for R&D purpose, but for production processes it would be too time consuming and complicated for an operator. Here a more robust analysis of the growth combined with a real-time statistical process control is needed. For industrial requirements, LayTec's EpiTT and EpiCurve® TT product families in combination with the EpiGuard® software package are applied. These in-situ systems provide a comprehensive and robust monitoring of growth parameters. Emissivity corrected pyrometry (ECP) has become the backbone of these metrology systems because crystalline quality, composition, and doping level highly depend on wafer surface temperature as it is measured on III-V, Si or Ge substrates by LayTec's integrated ECP modules.

The second key to high performance CPV epitaxy is the precise thickness monitoring of all layers during growth.

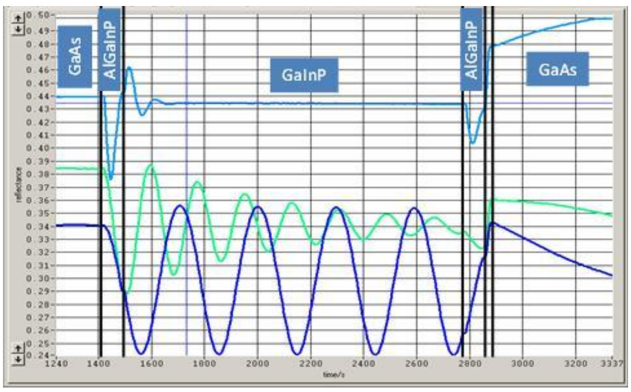

Fig. 3: Reflectance measurement of a multi-junction solar cell at three wavelengths: 950 nm, 633 nm, 450 nm (courtesy of Fraunhofer ISE Freiburg, Germany).

Fig. 3 is a screenshot of simultaneous reflectance measurement at 405 nm, 633 nm and 950 nm. Since the frequency of the Fabry-Perot oscillations decrease with increasing wavelength, the 950 nm measurement is used for thick layers deposited with a high growth rate. 633 nm are suitable for the measurement of thinner layers. Due to the absorption of shorter wavelengths in III-V materials, the reflectance measurement with 405 nm is highly surface sensitive and, therefore, beyond TJ thickness it also gives information on surface morphology and interface quality.

3. Curvature of III-V device structures

A further critical parameter is the wafer bow during and after growth. In the past, curvature measurements of lattice matched III-V device structures were thought to be obsolete because of the low strain growth of these materials. However, even in case of lattice matched growth, the curvature significantly increases after cool down due to the thermal mismatch between the substrate and the binary and ternary materials. Even more important is that pseudo-morphic and metamorphic growth techniques are used for advanced CPV structures, where the related strain engineering becomes a must. For the multi-junction solar cell production at Fraunhofer ISE, EpiCurve® TT has become a standard tool for strain management and process optimization. The heteroepitaxy of the III-V compounds on germanium leads to a significant bow of the wafer. It was found that the curvature in these applications is strongly aspheric (Fig. 4a) after intentioned buffer relaxation for metamorphic growth. LayTec's advanced resolution (AR) curvature technology enables the user to distinguish between spherical curvature and asphericity (Fig. 4b and c). The resulting signal helps to optimize the buffer growth and its relaxation at early and decisive stages of the epitaxial process.

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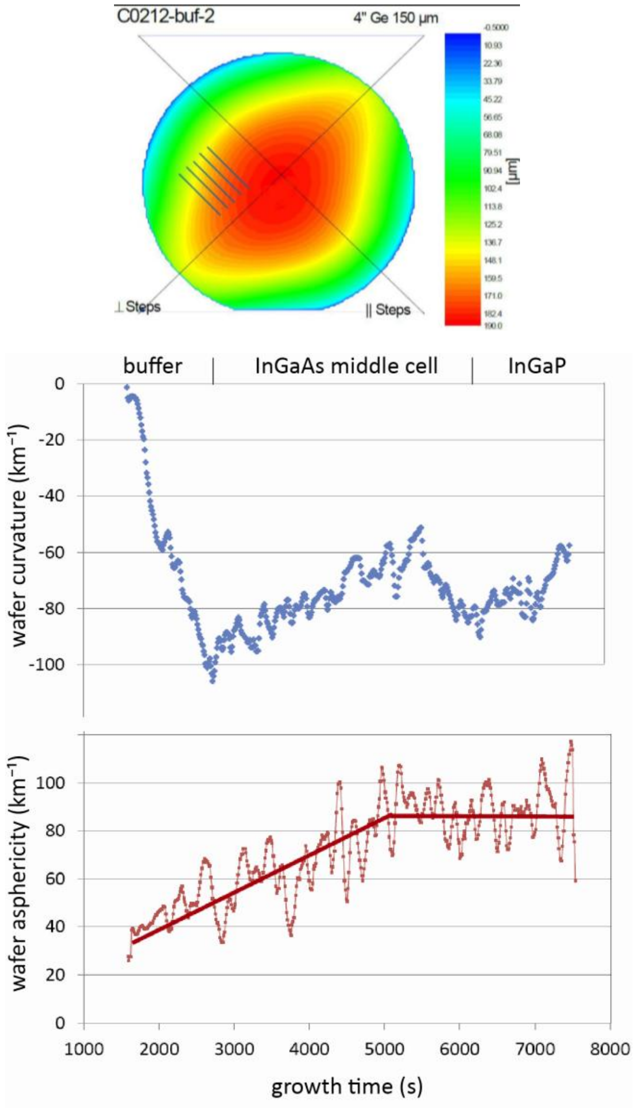

Fig. 4 a: Bow profile (ex-situ): aspherical bow perpendicular to the step edges of the off-cut Ge substrate.

Fig. 4 b: Wafer curvature measurements: strained InGaAs middle cell compensates metamorphic buffer bow.

Fig. 4 c: Wafer asphericity measurements by AR curvature measurements: asphericity starts with first pseudomorphic buffer relaxation.

With the current global trend towards even higher conversion efficiencies of CPV cells, more complex structures are being grown: inverted cells and 4-junction devices. Hence, the importance of in-situ metrology for CPV epitaxy is further increasing [1]. LayTec's mission goes far beyond supplying customers with cutting-edge in-situ metrology tools for process development and failure detection. Thanks to the close collaboration with an extensive R&D network, LayTec has gathered a huge know-how in analyzing and understanding in-situ data of epitaxial processes. This knowledge flows into the company's sophisticated software databases, into user trainings and suggestions for in-situ metrology based process optimization, yield improvement and, therefore, cost reduction.

For further information and consultation please contact info@laytec.de or visit www.laytec.de

Further reading:

[1] J.F. Geisz *et.al.* Journal of Crystal Growth **310** 2339-2344 (2008)

[2] W. Guter *et. al.* Applied Physics Letters **94** 223504 (2009)

[3]N.A. Kalyuzhnyy *et.al.* Proceedings of the 24th European Photovoltaic Solar Energy Conference (2009)

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