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Automated emissivity corrected wafer-temperature measurement in Aixtrons planetary reactors

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Abstract

A procedure and set-up for high-precision determination of the true surface temperature of wafers during growth by metalorganic vapour phase epitaxy is described. The reflectance of the surface measured by an *EpiRAS*® sensor is used for correcting the signal of a pyrometer for changes in emissivity. This allows for determination of the true surface temperature with a precision of ±1°C even for multilayer structures. This high precision allows to determine differences in the temperature of wafers of different size or rotating at different speed in an Aixtron Planetary Reactor®.

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1. Introduction

In MOCVD, the growth temperature is often the most important parameter because it influences the decomposition of the precursor gases, the growth process of the epilayers on the substrate surface as well as their physical properties. In consequence, the susceptor temperature is usually under tight control by using pyrometers or thermo-couple sensors. Recently, it became important for certain device growth processes to measure in addition also the real wafer surface temperature.

In this paper, we present recent results of a new, additional measurement mode for an *EpiRAS*® sensors that enhances the precision of the wafer-temperature measurement in a MOVPE Planetary Reactor™ to ±1°C and for the first time allows to log this key growth parameter for every individual wafer in a multiwafer reactor. This wafer-temperature measurement is performed in addition to the already well-established combined in situ reflectance anisotropy and reflectance measurements of the sensor which give access to key device parameters (layer thickness, composition, doping levels, stop band tuning, cavity resonance).

2. Experimental procedure

The measurement of the true wafer temperature is based on the direct communication of the

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EpiRAS® sensor with the process pyrometer. For this purpose, the pyrometer's optical detection system has been integrated into the optical head of the optical real-time sensor. The actual reflectance of the growing layer structure is measured exactly at the detection wavelength (950 nm) by means of an additional detector that has been integrated via a beam-splitter/950 nm filter configuration into the optical sensor head. This enables the fully independent operation of the temperature measurement and the measurement of the spectroscopic reflectance and RAS mode of the sensor.

The experiments have been performed in two different Aix 2600 multiwafer reactors. First, in the R&D laboratory of the Aixtron AG in Aachen the basic principles have been tested and the communication schemes between the real-time sensor and the MOCVD control system have been established. Second, at the Ferdinand–Braun Institute in Berlin at an Aix 2600 used for GaAs HBT growth, the performance of the new sensor module has been tested under real device growth conditions.

MOVPE growth has been performed at 650–680°C, 100 mbar and typically 24 slm hydrogen carrier gas flow. Standard sources like TMGa, TMAl and AsH_3 have been used. The reactor has been equipped with a standard planet for five satellites carrying 6″ and 4″ wafers side by side for comparison purpose.

3. Results and discussion

3.1. Calibration of the pyrometer

The pyrometer used is factory calibrated for a given optical pyrometer head and a given well-defined focus length. This factory settings of the pyrometer, however, could not be used because we had to design our own optical pyrometer head, fully integrated into the sensor optics. Hence, the focus length and detection angle were changed and we had to properly recalibrate the pyrometer.

For this purpose, we start with the standard equation of emissivity corrected pyrometry [1–3]:

$$\ln[P_L(T)] = \ln\left[\tilde{C}_1^{\mathrm{GaAs}}\right] - C_2\frac{1}{T},$$

$$\tilde{C}_1^{\mathrm{GaAs}} \equiv \xi \times \Delta\lambda\frac{2hc^2}{\lambda^5} \times (1 - R_{\mathrm{GaAs}}), \tag{1}$$

$$C_2 \equiv \hbar\omega/k_B$$

with ξ being a geometry parameter and R_{GaAs} being the bare substrate's reflectance. Eq. (1) allows for the pyrometric measurement of the temperature of bare GaAs wafers directly from the detected IR radiation power P_L. It can be shown that a geometry configuration different to the pyrometers standard configuration causes only an offset in $1/T$:

$$T_2 = \left[\delta\left(\frac{1}{T_{2,\mathrm{cal}}}\right) + \frac{1}{T_{2,\mathrm{factory}}}\right]^{-1}, \tag{2}$$

Hence, with this equation known, for a proper calibration of the pyrometer only the offset parameter $\delta(1/T)$ has to be measured at a single wafer temperature. We applied two different methods for calibrating the absolute temperature of the bare GaAs wafers in the reactors: (a) analysing the reflectance response during an AlAs–GaAs growth run that has a well defined and highly reproducible temperature dependence [4–5]; (b) by placing an Al–Si eutectic wafer into the reactor and measuring the reflectance response during a slow temperature ramp covering the 577°C eutectic temperature. The results are given in Fig. 1.

Once calibrated the true temperature measurement can be arbitrarily repeated if the focus conditions remain fixed. This is ensured by the fixed optical components on top of the reactor and the direct optical access to the susceptor surface free of any deposits during epitaxy.

3.2. Wafer temperature during the initial up-ramping of the reactor temperature

After the proper calibration of the pyrometer, we were able to directly sense the thermal emission from the wafers in the multiwafer reactors. We investigated the kinetic response of the wafer temperature during the initial up-ramping of the epi-ready, freshly loaded GaAs wafers.

These measurements show that the real wafer temperature is about 40°C below the 'process

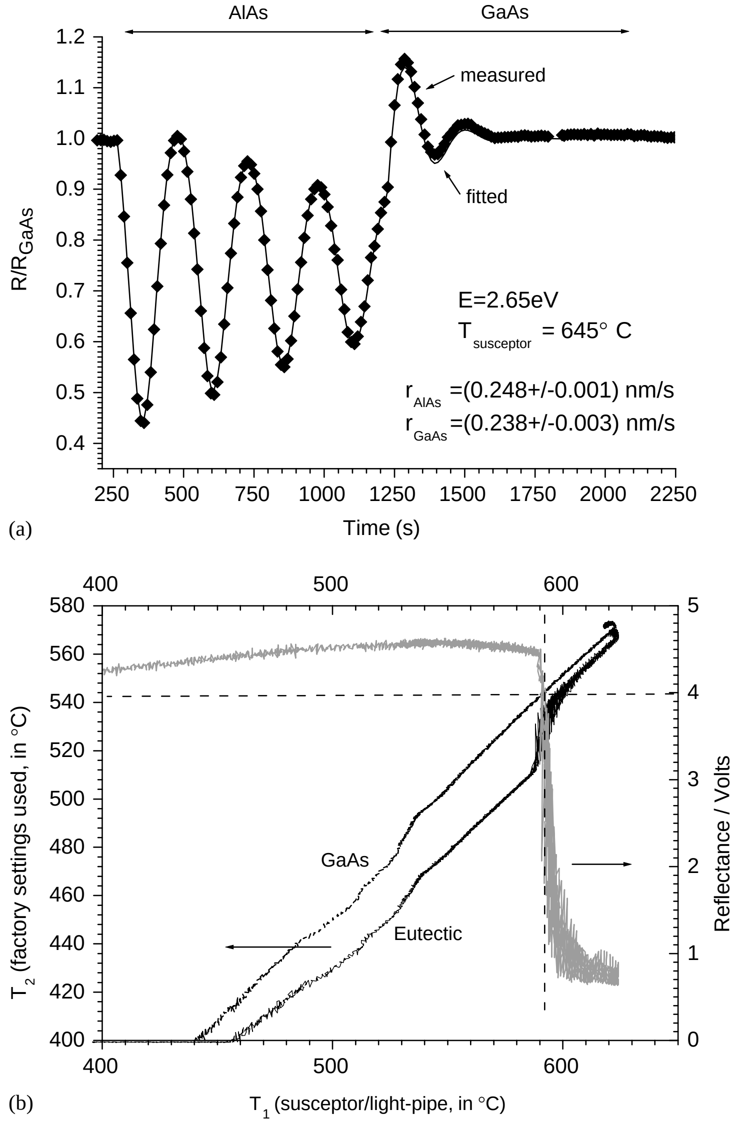

Fig. 1. In situ calibration of the pyrometer attached to a planetary reactor: (a) growth sequence of AlAs on GaAs. The reflectance transient was measured at a photon energy of 2.65 eV. From the depth of the first Fabry–Perot oscillation minimum during the AlAs growth a wafer temperature of 645°C was deduced. (b) Calibration of T_2 by means of reflectance monitoring on a Si–Al eutectic surface: The eutectic temperature of 577°C is observed at $T_{2,\mathrm{factory}} = 542°\mathrm{C}$.

temperature' of about 700°C measured by light pipe at the bottom of the susceptor. Looking to the time scale in Fig. 2, a slight delay in temperature response between the wafer temperature and process temperature during temperature ramps is discernable. The peak temperature on the wafer surface is reached some 10 s after the peak in the temperature of the susceptor bottomside. We refer this to the diffusion time of the heat flux from the bottom to the top of the graphite susceptor body.

3.3. Wafer temperature during AlAs–GaAs growth

For the continuos true wafer temperature measurement during an epitaxial growth sequence, the following reflectivity correction can be applied.

In the case that during epitaxial growth only the temperature output T_{uncorr} of a conventional pyrometer (with properly re-calibrated settings according to Section 3.1 but not using reflectivity corrections) is available, the following correction can be applied afterwards:

$$\frac{1}{T} = \frac{1}{T_{\mathrm{uncorr}}} + \frac{1}{C_2} \ln\left[\frac{(1-R)}{(1-R_{\mathrm{ref}})}\right] \tag{3}$$

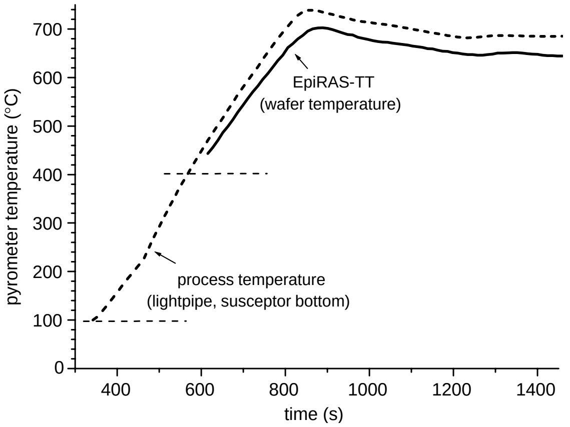

Fig. 2. Wafer temperature and susceptor temperature as measured during the initial heating ramp for oxide desorption at a 4″ GaAs(0 0 1) in an AIXTRON 2600 Gen-3 Planetary Reactor®.

with R_{ref} being the reference reflectivity (i.e. of the GaAs substrate) and R the measured one.

From Fig. 3 a wafer surface temperature of 645°C can be derived during the AlAs–GaAs-growth sequence continuously monitored by the calibrated and reflectivity corrected pyrometer.

3.4. Wafer temperature and susceptor surface temperature

The susceptor was loaded with four 6″ wafers and one 4″ wafer on satellite 2 for comparison. The 4″ wafer was rotating at a higher speed. The reactor was heated up and held at 600°C process temperature (light pipe). In contrast to the temperature measurements above, the assignment of the measured temperature data to the individual satellites was switched off. Thus, the complete circular temperature profile across all five satellites could be traced at once. Two different emissivities were applied for the susceptor and the wafers, respectively, because the emissivity of the susceptor differs from that of the substrates and may vary during the process. Fig. 4 shows the measured temperature profile.

Five different temperature informations can be derived: The wafer temperature T_{w} was 565 ± 2°C over all 6″ wafers. On any of the 6″ wafers the

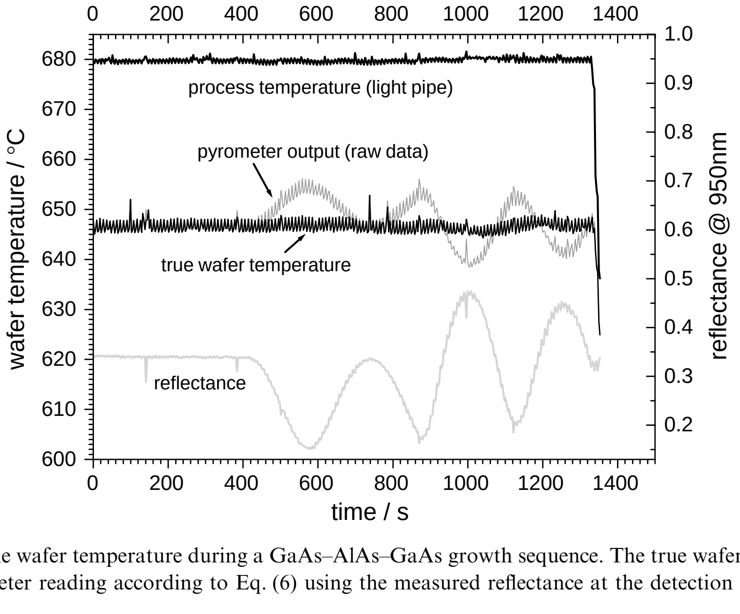

Fig. 3. Measurement of the wafer temperature during a GaAs–AlAs–GaAs growth sequence. The true wafer temperature results from a correction of the pyrometer reading according to Eq. (6) using the measured reflectance at the detection wavelength of 950 nm.

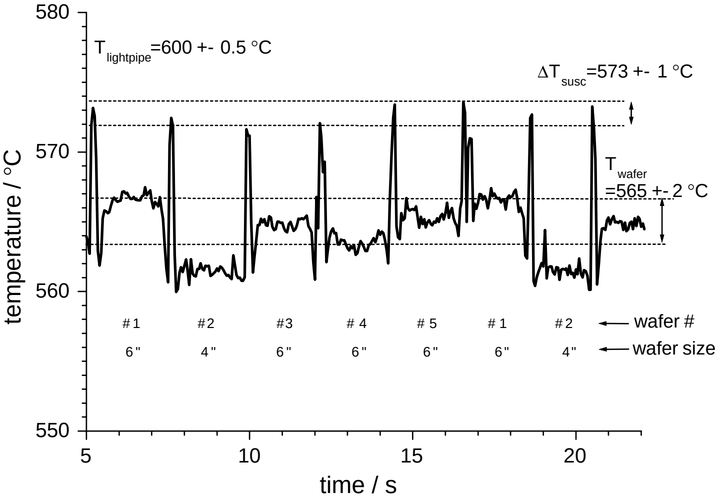

Fig. 4. Full 360° scan (during a full rotation of the planet) of the wafer and susceptor surface temperature in the planetary reactor.

temperature was within 1°C. The temperature of the susceptor body between the satellites was around 8°C higher than T_{w} on the neighbouring satellites. The 4″ wafer was about 3°C colder than the average temperature of the others showing the role of wafer weight and rotation speed to control the wafer temperature.

4. Summary

The following key advantages of a new, wafer resolved temperature measurement have been demonstrated at a standard Aix-2600 G3 Planetary Reactor™: (a) All three types of measurement, RAS, reflectance and wafer temperature, can be performed independently with high precision and without any cross-interference permanently throughout the growth process; (b) the pyrometer's output can be automatically and accurately calibrated by means of the reflectance measurement; (c) the absolute temperature of the wafers inside the reactor is measured, typically with a ±1°C sensitivity, because the emissivity oscillations due to Fabry–Perot thin-film effects can be corrected in real time by the *EpiRAS*® sensor system. Example measurements have been presented taken during the growth of GaAs/AlGaAs multilayer systems comparing the process temperature of the susceptor with the true wafer temperature. It is shown that the temperature uniformity from wafer to wafer in the Planetary Reactor® is excellent (better than 2°C).

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