Wafer temperature measurement methods: Band-edge detection vs. emissivity corrected pyrometry

For in-situ temperature measurements in MOCVD, MBE and other thin film techniques, two different optical methods are applicable: emissivity corrected pyrometry (ECP) and band-edge detection measurements (BED). The ECP method is applied in all of LayTec 's TT sensors like EpiTT, EpiR TT and EpiRAS TT, while band-edge detection measurements are only possible with spectroscopic reflectometers covering the spectroscopic range of band-edge of the growing material (like EpiR or EpiRAS). In this document, both methods are compared and advantages and disadvantages of both methods are discussed with respect to typical applications.

In general, the ECP method works much better for higher growth temperatures and has the advantage of a wider application range, even during hetero-structure growth and on various substrates. The BED method, on the other hand, is the only method applicable for very low temperatures (RT-200°C).

Temperature measurements on bare substrates

A direct temperature measurement on the bare substrate is often used in order to calibrate the temperature offset between the process temperature (e.g., thermo-couple) and the real wafer temperature. The applicability of the BED method is limited in many cases for the following reasons:

a) bare sapphire substrates, having a band-edge in the UV, can not be measured;

b) pseudo-substrates (e.g., GaN templates on Sapphire) can not be measured accurately because of the strain effects to the band edge position;

c) typical band-edge (E_g) monitors work only for not too high doping levels because higher doping levels ($>1\cdot10^{18}cm^{-3}$) cause band-edge shifts and free-carrier absorption;

d) at intermediate temperatures (~500-650°C) the accuracy BED measurement suffers due to thermal broadening;

e) At higher temperatures (>~650°C, depending on the type of substrate) the BED method is often not applicable because of the absorption of thermally generated free carriers.

The following table compares the ECP- and BED-Method for different substrates:

Material	**ECP-Method**	**BED- Method**
ZnSe, ZnTe, SiC and other transparent substrates	400-1400°C*	RT-700°C
Sapphire and other UV-transparent substrates	400-1400°C*	not applicable
GaN substrate and other transparent substrates where E_g depends on strain	400-1400°C*	not applicable
GaAs, InP, Si (undoped)	350-800°C	RT-650°C
GaAs, InP, Si (doped > 10^{18} cm^{-3})	200-800°C	not applicable

* with proper calibration, because only the susceptor surface (MOCVD) or sample holder surface (MBE) radiation from just below the wafers can be measured

Temperature measurements during hetero-structure growth

During hetero-epitaxy there are even more effects limiting the applicability of BED temperature sensing: when layers are grown having band-edge energy below the substrate, the light necessary for measuring the substrate band-edge is simply absorbed. In this case the BED method suffers as soon as the thickness of the growing layer reaches the penetration depth of light at the band-edge energy E_g of the substrate. But even growing transparent layers cause artefacts to the BED temperature due to the distortion of the band-edge signature by Fabry-Perot oscillations.

Material	**ECP-Method**	**BED- Method**
Growing layers having high E_g compared to substrate e.g. AlGaAs/GaAs	works well	works, but with reduced performance
Growing layers having low E_g compared to substrate e.g.: InGaAsP/InP, AlGaInP/GaAs, GaInAsN/GaAs	works well	works, but only for thin absorbing layers

The ECP method, however, always gives a stable non-oscillating temperature signal during hetero-epitaxy because the emissivity correction completely removes the Fabry-Perot oscillation artefacts.

Temperature measurements under specific growth conditions / specific MBE or MOCVD set-ups

BED temperature sensing through a single optical port is only applicable in some MBE configurations where the thermal radiation of the heating system behind the substrate can be used as 'light-source'. This, however, only works when the radiation out of the wafer is much weaker than the radiation of the heater. So a 'bad thermal contact' between the 'cooler' wafer and the 'hotter' sample holder is required for good measurements - but this is not really a perfect situation for reproducible growth. The work-around solution for this is usually a second view-port for additional white-light illumination. But even this fails when the back-side of the wafer is polished and therefore not scattering the white-light back through the wafer.

Growth and substrate heating conditions	**ECP-Method**	**BED- Method**
Double polished wafers good thermal contact	works well	not applicable
Substrates with rough backside good thermal contact between wafer carrier and substrate	works well,	Second view-port needed!
Substrates with rough backside bad thermal contact between wafer carrier and substrate	works well	works well
IR-radiation from surrounding e.g. MBE sources, or view-port heating	Works well after software correction for off-set	Works well

Temperature sensitivity

Because of the different physical principles behind band-edge detection (BED) and emissivity corrected pyrometry (ECP), the temperature sensitivity is changing differently with the wafer temperature. The accuracy of BED is at its best at room-temperature where the band-edge is not yet thermally broadened. ECP is completely 'blind' at room-temperature, because no black-body radiation is emitted by the wafer in the detected spectral range.

This advantage of BED holds for temperatures between RT and ~200°C. At 200°C advanced ECP systems reach already the same sensitivity as BED sensors. With further rising wafer temperature, the sensitivity of BED systems becomes increasingly poorer because of thermal band-edge broadening, while the sensitivity of ECP sensor rises - according to Plack's equation - exponentially.

Temperature range	**ECP-Method**	**BED- Method**
RT-200°C	not applicable	± 2K
200- 400°C	± 3K	± 3K
400-650°C	± 1K	± 5K
650-1300°C	± 0.5K	not applicable

To summarize:

The BED method is only advantageous in the following special case: low temperature growth of high-band-gap materials on undoped, low-band-gap substrates or for offset-calibration (e.g., between thermo-couple and wafer temperature) on bare, undoped, non-UV-transparent substrates at not to high temperatures.

In all other cases the ECP method is a considerably better choice.

The basic principles of ECP [i] and BED are further described in [ii]

[*i*] LayTec True Temperature Information Note: http://www.laytec.de/faq/info_true_temperature_method.pdf

[*ii*] S.R. Johnson, C. Lavoie, T. Tiedje, J.A. Macenzie, "Semiconductor Substrate Temperature Measurement by Diffuse Reflectance Spectroscopy in Molecular Beam Epitaxy", J.Vac. Sci. Technol. B11(3), May/June 1993; 1007-1010