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Technical Note

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The truth behind today's wafer temperature methods:

Band-edge thermometry vs. emissivity-corrected pyrometry

TODAY'S OPTICAL TEMPERATURE MONITORING OPTIONS EXPLAINED

- **Current Band Edge Technology compared with Emissivity Corrected Pyrometry**
- **Evaluated for MBE, MOCVD, and general semiconductor wafer temperature monitoring**
- **Data and references taken from released vendor documentation**

Introduction & Motivation

Recently, two leading in-situ temperature measurements for MOCVD, MBE, and other thin film techniques have emerged. The two methods are emissivity-corrected pyrometry (ECP) and band-edge thermometry (BET). Both methods are non-contact, non-invasive measurement techniques.

The purpose of this document is to evaluate the current state of the art with respect to both methods while discussing advantages and disadvantages of both methods with respect to typical applications.

Emissivity Corrected Pyrometry relies upon measuring the radiation intensity from a substrate. Planck's equation for black body radiation distribution is employed, and a laser or led is used to monitor reflectance changes for compensating interference oscillations at the pyrometry wavelength being used.

Band-Edge Thermometry utilizes the temperature-dependent absorption edge of semiconductor materials to determine substrate temperature. The absorption edge position is directly related to the band gap energy of the material, which, in turn, is temperature dependent.

While both empirical and theoretical equations exist for band gap dependence on temperature for most materials of interest, in practice these equations do not consider doping effects, scattering, and instrument response. As a result, it is much more accurate to generate experimental calibration curves or lookup tables that map a measured absorption edge wavelength to a previously calibrated temperature value. k-Space has developed an empirical method for calibrating the band edge temperature dependence of a particular material with that of a blackbody calibrated thermocouple directly mounted to the sample. Subsequent temperature measurements using the BandiT system are based upon this direct temperature vs. band edge relationship.

Temperature measurements on bare substrates

Direct temperature measurement of the bare substrate is often used to calibrate the temperature offset between the process control temperature (e.g., thermocouple to control heater PID loops) and real wafer temperature.

GaAs, InP, Si substrates. While both ECP and BET work well for GaAs, InP, and Si substrates, the general usable temperature range is limited with each. While ECP can typically measure temperatures from 450°C and higher, BET can measure from RT-700°C, and is limited by free carrier absorption and black body radiation at higher temperatures. For temperatures greater than 700°C, an integral pyrometer has been implemented with BET via monitoring radiation intensity at any wavelength (and multiple wavelengths) within the spectrometer range. Note that the traditional drawbacks to pyrometry still apply to ECP: viewport coating, stray light from hot sources, reflection off chamber walls, and heater radiation cause significant measurement error with ECP. Emissivity correction does nothing to improve on this problem as it is still an intensity-based measurement technique. In contrast, BET is not effected by viewport coating or stray light whatsoever as it is a position-based measurement (not intensity-based).

GaN, SiC, ZnO, SrTiO3 substrates. ECP cannot measure the temperature of these substrates, as they are wide band gap materials and hence transparent at the wavelengths used by ECP. For these materials, ECP measures the temperature of the substrate holder, susceptor, or heater. BET can accurately measure temperature on these substrates from RT thru 1200°C. Higher temperatures can be reached with these substrates because, due to the larger band gap, the absorption edge is further in the visible/N-UV and as such is not washed out at high temperatures by free carriers and black body radiation.

The following table compares ECP and BET for typical substrates used in today's semiconductor processes.

Substrate Materials	BET	ECP
GaN, SiC, ZnO, ZnSe, ZnTe and other transparent semiconductor substrates.	Works well from RT-1200 °C.	Cannot measure substrate temperature directly.
Sapphire and other UV-transparent, Insulating Substrates.	Cannot measure substrate temperature directly.	Cannot measure substrate temperature directly.
GaAs, InP, Si (doped > 10^{18} cm^{-3})	Works well from RT-700 °C with new spectra processing techniques. Integral multi-wavelength pyrometer used above 700 °C.	Works well from 400-1300 °C. Subject to error from coated view-ports and stray light.
GaAs, InP, Si (Semi Insulating)	Works well from RT-700 °C. Integral multi-wavelength pyrometer used above 700 °C.	Works well from 400-1300 °C. Subject to error from coated view-ports and stray light.

Temperature measurements during heterostructure growth

Materials	BET	ECP
Growing layers having high Eg compared to substrate e.g. AlGaAs/GaAs	Works Well	Works Well
Growing layers having low Eg compared to substrate e.g.: InGaAs/InP	Works well up to ~1.2µm of lower Eg material. Integral multi-wavelength pyrometer used > 1.2µm thickness.	Works Well

While not affecting ECP, the material properties of the growing layers during heteroepitaxy may affect BET signal. The signal required for BET is reduced when layers are grown having a smaller band gap energy than the substrate. However, this signal degradation does not affect the temperature measurement until about 1.2µm of lower band gap material has been deposited. At that time, the BET monitor can be used in multi-wavelength pyrometry mode, calibrated at the last BET temperature observed to ensure temperature continuity. For equal or higher band gap material deposition, there are no limitations within the temperature range for either BET or ECP. Another concern with heterostructure growth is the phenomena of pyrometric interference oscillations. As a result, apparent temperature oscillations during deposition are seen with standard pyrometry measurement. By correcting for emissivity changes using a laser or LED, these oscillations can be minimized with ECP. With BET, these oscillations are not as strong because, again, the measurement is position-based as opposed to signal-based. However, apparent temperature oscillations can be seen. These oscillations can be minimized by using a 2nd-derivative analysis for band-edge detection (deeper in the absorption portion of the spectra) instead of the standard linear fit to the absorption edge.

Growth and Substrate Heating Conditions	BET	ECP
- Double polished wafers - Good thermal contact	Works well with graphite substrate holder or rough backing plate.	Works Well
- Substrates with rough backside - Good thermal contact between wafer holder and substrate	Works Well	Works Well
- Substrates with rough backside - Bad thermal contact between wafer carrier and substrate	Works Well	Works Well
- IR-radiation from surroundings, e.g. MBE sources, substrate heater, or heated view port	Works Well	Poor. Software correction only valid for steady state radiation.

Temperature measurements under specific growth conditions

BET temperature sensing can be used without a light source when the thermal radiation of the heating system under the substrate is sufficiently more intensive than the radiation from the wafer itself. For lower temperature operation, a light source may be added to increase the signal. Thermal contact with the heater and wafer does not effect the BET measurement, but any stray heater radiation that is comparable with the substrate heater radiation will affect the ECP temperature dramatically, leading to false high temperature readings. While DSP substrates reduce the amount of BET signal due to backside specular reflection, sufficient signal is obtained for accurate temperature measurement.

Temperature Sensitivity

Because of the different physical principles BET and ECP, the temperature sensitivity is different for each when operating within different temperature regimes. ECP is completely "blind" at low temperatures, because no black body radiation is emitted by the wafer in the detected wavelength until about 450°C. With new solid state spectrometers and state-of-the-art spectral processing routines, the past limitations with BET temperature sensitivity at higher temperatures have been overcome.

Temperature Range	BET Resolution	ECP Resolution
RT-450°C	GaAs InP, Si: ± 0.1°C GaN, SiC, ZnO: ±1.5°C	No Signal
450-690 °C	GaAs InP, Si: ± 0.2°C GaN, SiC, ZnO: ±1.5°C	± 1 °C
690-1300 °C	GaAs InP, Si: No Signal GaN, SiC, ZnO: ±1.5°C	± 0.5°C
Reproducibility	GaAs InP, Si: 1% GaN, SiC, ZnO: 2%	Very Poor Run to Run

Summary

Recent improvments in Band Edge Thermometry (BET) technology have been compared with current Emmissivity Corrected Pyrometry (ECP) technology, illustrating the benefits and limitations of optical temperature measurement on today's semiconductor wafers. While limitations exist with each technology, further improvements in hardware and software designs are expected. Each application may be chosen carefully based upon material, temperature range and reproducibility requirements within the process.

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