



True Temperature measurements: the physical background

During epitaxial growth the wafer temperature is one of the key parameters. It influences such elements as growth rate, composition of ternary and quaternary compounds and doping levels. Wafer temperature also has an important impact on the quality of the grown layer and its roughness and thereby on the performance of devices based on such epitaxial layers. Thus, careful monitoring and precise control of wafer temperature during the whole growth process are indispensable. Usually the temperature is controlled indirectly, either by thermocouples or by pyrometers.

As thermocouples are mounted on or light-pipe pyrometers are directed to the backside of a wafer holder they do not necessarily measure the temperature of the wafer accurately. Limited thermal contact between the sample holder and the wafer, along with the enhanced cooling of the wafer across its surface, might be the reasons for temperature differences. This difference can vary for distinct types of wafers or – especially in some MOCVD systems– depend upon gas flow and sample rotation frequency.

In contrast to thermocouples, optical pyrometry measures the temperature directly at the wafer surface or the growing layer. So, whenever there is a need to carry out contact-free temperature measurements, pyrometry is the method of choice. It relies upon the fact that all bodies at temperatures above absolute zero emit electromagnetic radiation, the so-called thermal radiation. Therefore it is possible to derive the temperature of a body by measuring the intensity of this radiation. In addition, especially in heteroepitaxy, the emissivity changes during the growth process.

The relation between the emitted radiation of a body at a certain wavelength and the temperature is given by Planck's law. It was derived by Max Planck in 1900 to describe the spectral density of radiation of a black body (which marks the beginning of quantum physics as on that occasion for the first time ever the quantization of energy was postulated)

The incandescence intensity of a black body is given by:

$$dP_s = 2/h^4 c^3 * (\hbar\omega)^5 / e^{\hbar\omega/k_B T - 1} * d\lambda$$

In Figure 1 this relation is shown for different temperatures. Thermal radiation mainly occurs in the infrared up to the visible part of the electromagnetic spectrum. The emitted radiation power, i.e. the area below the curve, increases with the rising temperature. Also the maximum of the incandescence intensity shifts towards smaller wavelengths, i.e. to higher photon energies with increasing temperatures.

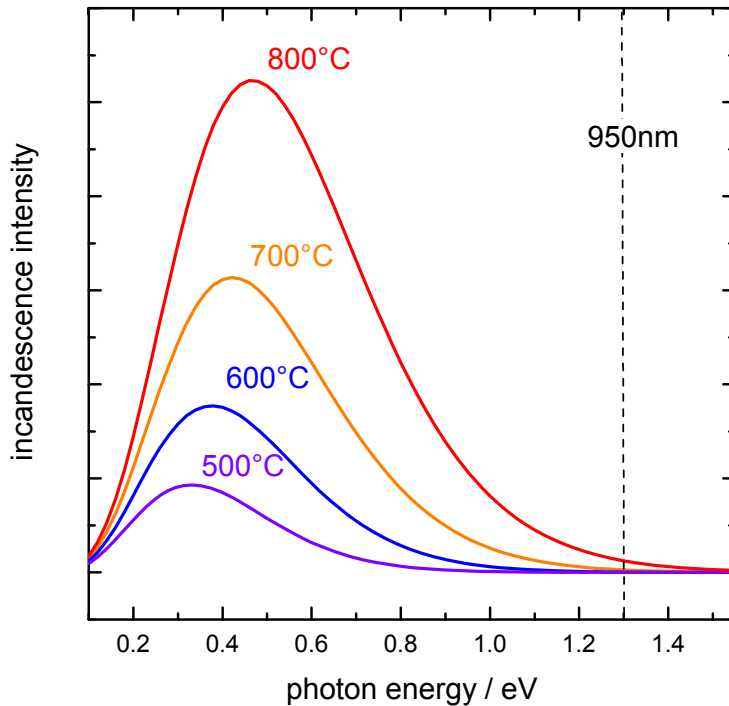


Fig. 1: Emission of a black body according to Planck’s law: the emitted radiation power increases together with the temperature, the maximum of the curves shifts to higher photon energies.

However, estimating the temperature of a real body following Planck’s law will lead to a large error. Why? Usually it is assumed that all incoming radiation is fully absorbed independently of its wavelength. The same accounts for the emission of radiation. But this is only true for ideal black bodies, whereas real bodies have a limited absorption/emission depending on the optical properties of the material at different wavelength as well as on the surface roughness. Therefore a simultaneous measurement of the reflectivity of the sample is indispensable to perform the correct measurement. The difference between the emission of a real body (P) and that of a black body (P_s) is described by the emissivity

$$\epsilon(\lambda,T) = P / P_s.$$

$\epsilon(\lambda,T)$ gives the ratio of the emitted radiation with respect to that of a black body. Thus, in order to estimate the emission of a real body, Planck’s law has to be corrected by the emissivity.

$$dP = \epsilon * dP_s = \epsilon * 2/h^4c^3 * (\hbar\omega)^5/e^{\hbar\omega/k_B T - 1} * d\lambda$$

In order to derive the temperature of a sample by measuring its incandescence intensity, the emissivity has to be measured as exactly as possible.

During growth processes such as MOCVD and MBE the emissivity often changes. One reason is the shift of the electronic band gap of a material with respect to temperature. During heteroepitaxy the measured incandescence intensity may also be influenced by different optical properties (e.g. band gap, refractive index) of the distinct material layers, respective substrates and layers. Furthermore, the thermal radiation undergoes reflections at the surface and the interfaces between the different layers, which leads to constructive and destructive interference effects. This results in a significant modulation of the emitted intensity, depending on the thickness of the growing layer (figure 2, lower part, blue line). Whereas in reflectance measurements this effect may be used to estimate the growth rate, in pyrometry it results in a false signal or non-existing change in temperature.

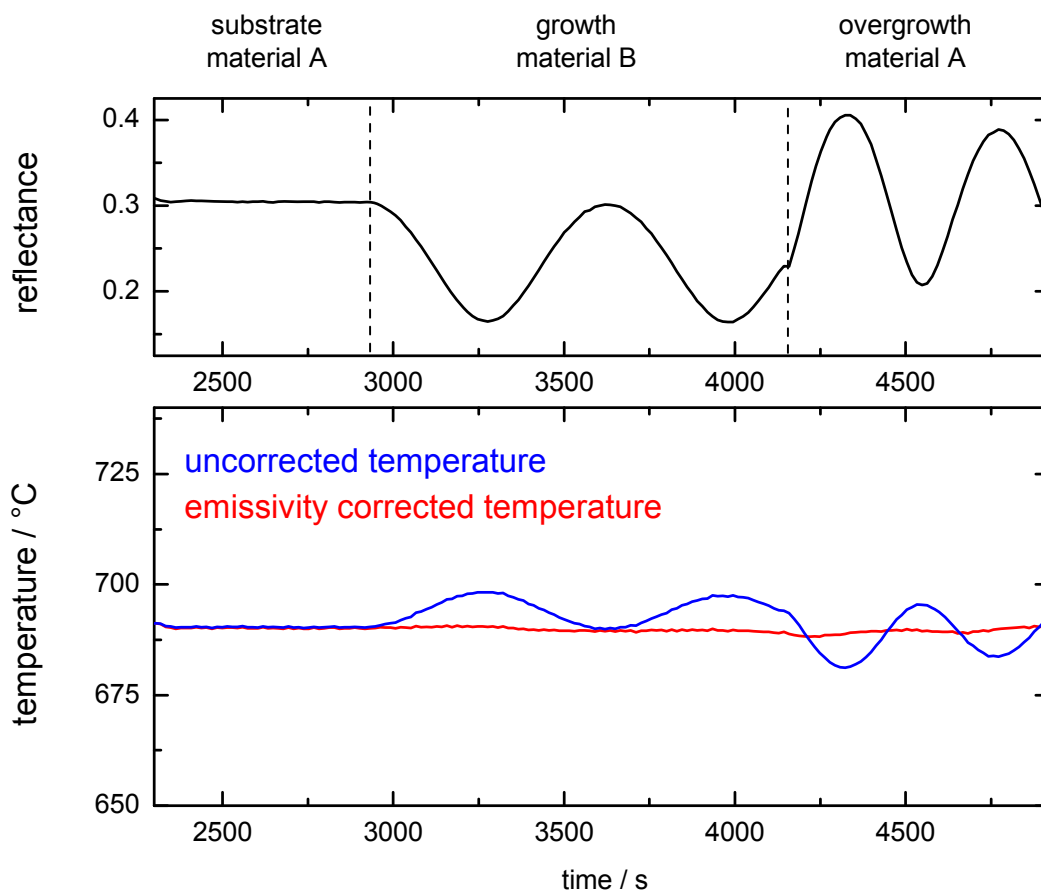


Fig. 2: True Temperature measurement during heteroepitaxy: Reflection of the thermal radiation at interfaces leads to interference and thus to an intensity modulation, depending on the layer thickness in the pyrometry measurement (blue curve). The true wafer temperature is given by a correction according to an additional measurement of reflectance at the same wavelength (black curve).

In order to measure the temperature correctly in spite of all these effects, reflectance measurements at the same wavelength as pyrometry are indispensable to determine the actual emissivity of the wafer. Therefore the wafer is illuminated and the intensity of the reflected beam is measured. Because of the conservation of energy the sum of absorbed, reflected and transmitted radiation has to be equal to that of the incident light. This means: absorption coefficient α , plus reflectance coefficient R , plus transmission coefficient equals one. For opaque materials no transmission takes place. In such cases the absorption can be easily derived from the reflectance by the equation:

$$\alpha = 1 - R$$

Since according to Kirchhoff's Law the absorption equals the emissivity of a body

$$\alpha(\lambda, T) = \varepsilon(\lambda, T),$$

the emissivity can be easily derived from the reflectance measurement. Then it will be possible to measure the true temperature using Planck's Law. However, it should be noted again that proceeding in this way is only possible if the substrate under investigation is completely opaque and smooth, as roughness will lead to scattering losses in the reflectance signal.

It is more difficult to perform a reliable temperature measurement if a transparent substrate is used (as for example SiC or Sapphire for growth of GaN). In this case the pyrometer does not measure the temperature of the wafer but that of the underlying wafer carrier, their difference being ΔT . This difference is estimated by a calibration according to the following procedure: First the absolute temperature of the wafer carrier is determined (e.g. by a melting point measurements, eutectics or pyrometry at two different wavelengths). Then the temperature of the substrate is determined from its optical properties (e.g. by analysing the position of the band edge of the substrate in spectroscopic reflectance measurements). These two measurements together give the difference in temperature ΔT between the wafer holder and the specific type of IR-transparent substrate used, which in turn can be applied to correct the temperatures by pyrometry during the epitaxial process.

LayTec's in-situ sensors **EpiTT**, **EpiR TT** and **EpiRAS TT** are all capable of an accurate true wafer temperature measurement based on the methods described above.