N O V E M B E R ,   2 0 0 8

New Technology Note

k-Space Associates, Inc

NEW! kSA BandiT Blackbody Temperature Measurement

NOVEL TEMPERATURE MONITORING TECHNOLOGY

- **Measures Black-body emission spectra directly from sample**
- **Real-time fitting to Planck's equation**
- **Better than 0.1°C resolution from 300°C and higher!**
- **In-situ calibration via standard BandiT band-edge measurement**
- **Spectrometer-based with λ range tailored to materials measured**
- **No need for emissivity corrections during growth!**
- **Fully integrated with existing kSA BandiT software and hardware**

Introduction & Motivation

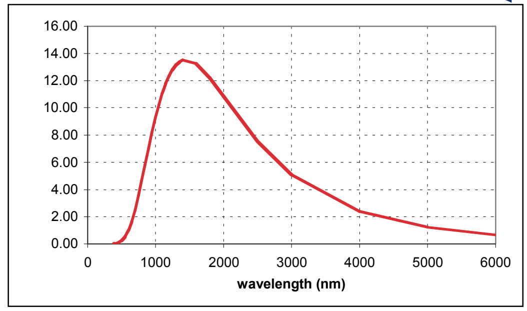


Figure 1: Blackbody emission of opaque sample at 2000K (1727 C)

Many of today's advanced electronic and optical devices are manufactured using thin film and semiconductor deposition processes. On a production level, ultimate device performance and reproducibility of these devices are often directly linked with the ability to control substrate temperature with high precision and repeatability during every step in the deposition process. Traditionally, many of these processes use a form of pyrometry for temperature determination. Specifically, the detected radiation intensity in a specific wavelength range is related to the sample temperature via a fundamental relationship between emission signal and sample temperature. For a given temperature, these emission characteristics over all wavelengths (i.e. blackbody spectrum - (BB)) obey Planck's Law, in that the intensity at any wavelength I(λ) is given by:

$$I(\lambda) \sim (K/\lambda)^5/[\exp(hc/\lambda kT) - 1]$$

which, when plotted, looks like the chart shown in Figure 1 (for a sample temperature of 2000K (1727C). At a fixed wavelength, the intensity varies roughly exponentially with temperature (as shown in Fig 2, for 1300nm), and this relationship forms the basis of standard pyrometry, which relies on measuring the integrated light intensity for a fixed time period over a narrow wavelength range. This approach assumes (1) no changes in sample emissivity, (2) the sample is opaque at the measurement wavelength, and (3) no other intensity contributions or attenuation from non-sample related sources (i.e. viewport coatings, stray filament radiation, etc.). However, these assumptions fail to cover most of today's semiconductor processes that require consideration for stray light, emissivity changes during deposition, or viewport coatings. Also, some type of in-situ calibration is required on a routine basis to ensure chamber -dependent factors are compensated for. When monitoring temperature of semiconductor materials, it is also important to collect signal intensity information for pyrometry at a wavelength where the material is absorbing (i.e. above material band gap or 'band edge').

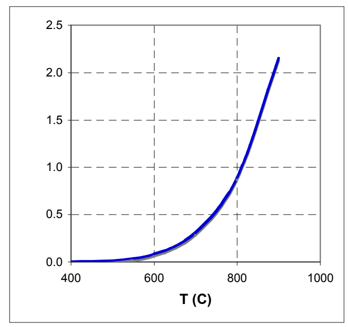


Figure 2: Emission intensity vs. wavelength at 1300nm

k-Space has developed a novel temperature monitoring technique for collecting this radiation intensity (blackbody emission) across a broad wavelength range that yields significant advantages compared to standard pyrometry. By using a solid state spectrometer and advanced real-time processing algorithms, the kSA BandiT blackbody measurement technique fits, in real-time, the entire radiation intensity vs. wavelength curve of a sample to Planck's equation. As shown in Figure 3, temperature information is taken directly from the opaque spectral region of the semiconductor material, above the material's band gap. In-situ calibration is typically made via band edge measurement either directly via observed spectra, or after the blackbody signal has been removed from the measurement (a standard feature now included with kSA BandiT). After single point calibration is performed to match Planck's equation at a given temperature, any further changes in temperature will be detected by fitting to the blackbody emission curve. kSA fits these curves in real-time to accurately determine surface temperature.

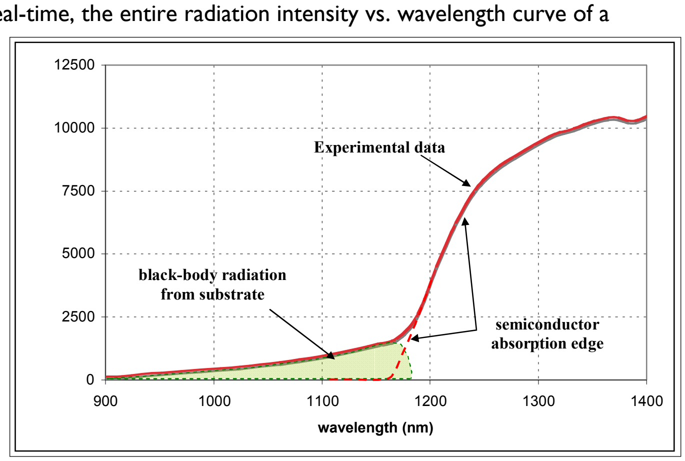


Figure 3: Blackbody emission from a semiconductor material follows Planck's Law: the valid portion of the curve is dependent upon temperature and band gap.

Standard Pyrometry vs. Blackbody Fitting

Any form of pyrometry collects radiated signal at a given wavelength and surrounding wavelength range (collection window). Commercial pyrometers typically use a collection window in the NIR range of 930-970nm (950nm +/- 20nm) as shown in Figure 4. This provides the necessary signal intensity for most common substrates from 450°C and higher. Below ~450°C not enough radiation density can be collected to obtain a stable measurement. Other conventional pyrometers can use other collection windows that are farther to the right of the blackbody radiation curve (longer wavelengths) in efforts to improve lower-end performance. However, this approach suffers from increased effects of stray NIR radiation such as heater filaments, plasmas, and other sources that may emit radiation in the >1um range.

kSA blackbody technology allows sample radiation intensity to be collected anywhere within the range of a solid state spectrometer, and integrated over any desired wavelength range. The new software fitting routine fits the shape of the experimental data curve to Planck's equation over a range of wavelengths set by the user – all in real-time by using a least squares fitting routine (as shown in Figure 5 during 850°C blackbody source emission). By fitting this curve to Plank's equation over the entire spectrum, the resulting temperature calculation is only dependent upon changes that affect the entire spectral range, which would lead to a shift in the entire emission curve. Localized intensity changes at particular emission wavelengths do not affect the curve fitting position itself and subsequently, temperature remains stable and accurate.

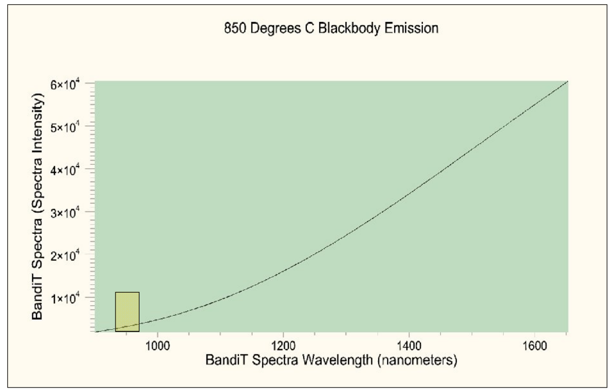


Figure 4: Standard pyrometry intensity collection window (950nm +/- 20nm).

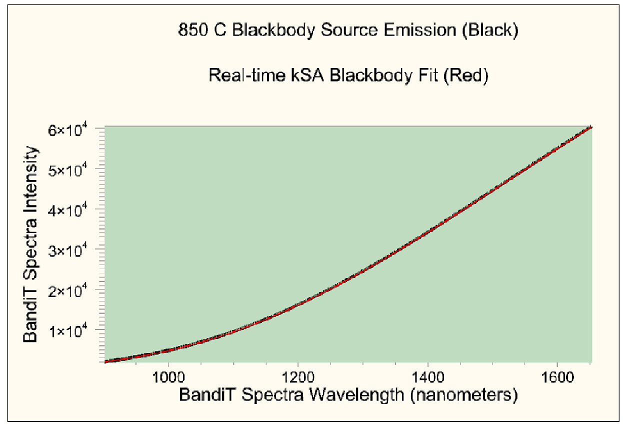


Figure 5: kSA BandiT collects intensity over a broad spectral range and fits Planck's equation in real time to determine temperature.

10x Higher Temperature Resolution

Since kSA BandiT is collecting radiation over a wide spectral range (material dependent), the integrated magnitude of the collected signal, when accumulated over the appropriate integration period, is very high. Since kSA BandiT is not limited to a narrow band of intensity collection (as with pyrometry), fitting routines have proven to be very stable for real-time fitting of Planck's equation, even at low sample temperatures. This, combined with auto-integration control from 1-300 msec, ensures the highest S/N observed for any intensity-based temperature monitoring system, leading to 10x higher temperature resolution. As shown in Figure 6, kSA BandiT was used to monitor the blackbody emission from a NIST (National Institute of Standards & Technology) calibrated blackbody source at 850°C and output a corresponding temperature based upon the real-time fit. By using a collection range of 900-1550nm, a temperature resolution of better than 0.05°C was easily obtained. Even at temperatures below 400°C, temperature resolution has been shown to surpass 0.1°C. At higher temperatures (>850°C), most semiconductor materials can be measured with the BB technique to better than 0.05°C resolution. Typical data acquisition rates are between 1-5msec for these temperatures, allowing for spatially resolved temperature measurement (wafer-to-wafer and within wafer) even during high speed multi-wafer substrate rotation.

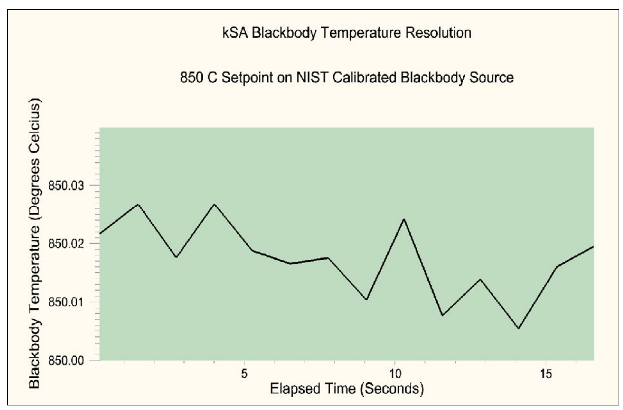


Figure 6. kSA blackbody temperature measurement yields better than 0.1°C resolution at 850°C.

kSA Blackbody Temperature Measurement During Growth

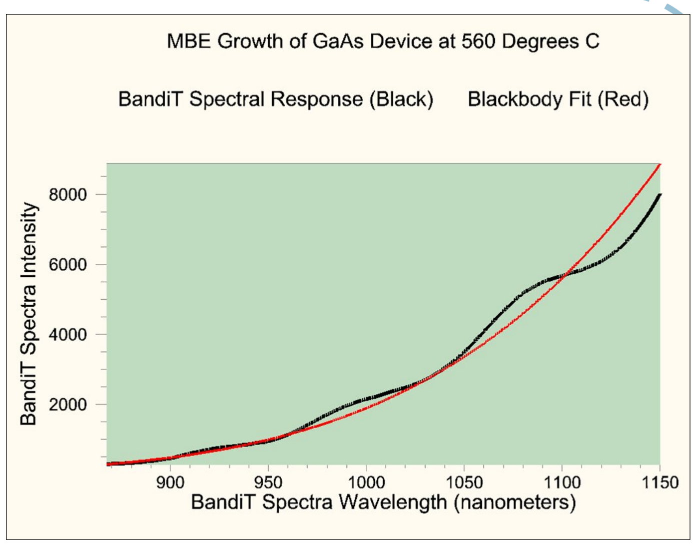
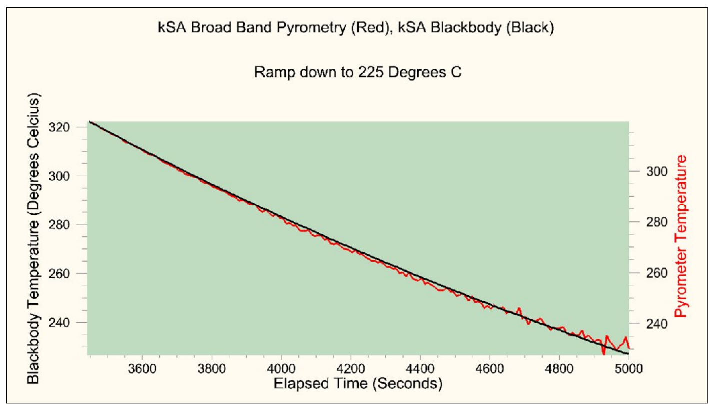


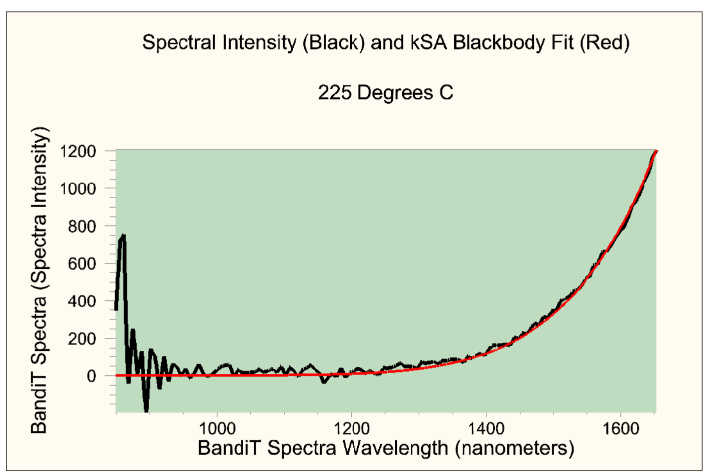
Figure 7: Spectral interference fringes propagate during heteroepitaxial growth. kSA BandiT fits through localized changes in emissivity and/or intensity, and hence the temperature remains stable.

Intensity-based temperature measurements (i.e. pyrometry) are susceptible to thickness oscillations due to interference effects in heteroepitaxial films (AlGaAs on GaAs, etc.), giving rise to apparent oscillations in the measured temperature. This can be seen in propagating intensity changes vs. wavelength during film growth. If the kSA BandiT spectral collection range is wide enough to include one or more periods of these interference fringes (if present), there is an inherent averaging which dramatically reduces the effect on the measured temperature. As shown in Figure 7, the blackbody fit will only change based upon a uniform intensity shift across all wavelengths. Similar considerations apply during plasma assisted processes such as PECVD or RF MBE, where sharp plasma lines could have a strong effect on single-wavelength measurements. But, since kSA BandiT fits over the entire collection spectrum, these effects are localized and not introduced into the measurement.

Low Temperature Deposition



Figures 8 & 9: kSA BandiT broad band pyrometry and BB ramp down to 225C (above). Blackbody fit at 225C (below).



Most traditional pyrometers are limited to single wavelength collection windows for obtaining signal information, resulting in a lower limit for temperature measurement of ~450°C. Since kSA BandiT collects intensity over a large spectral range where the sample is absorbing, the lower temperature limitation is extended and remains stable to below 300°C for most semiconductor substrates. Figure 8 shows a calibrated NIST blackbody source temperature ramp down to 225°C during simultaneous temperature measurement using broad band integrated pyrometry (900-1550nm intensity collection window) and blackbody measurements (simultaneous measurements are now available with kSA BandiT). Even when the intensity collection window for pyrometry is expanded to cover a very large range to maximize signal level, the measurement becomes noisy below 300°C. However, since the blackbody temperature measurement is an accumulated intensity curve fitting approach, we can use auto-integration of the intensity collected and fit over the entire spectral range to maintain proper measurement and resolution down to 225°C. Figure 9 illustrates the signal available at this temperature and the resulting blackbody fit at this lower temperature. While this data was acquired using an ideal blackbody source (emissivity value of 0.99 and fully opaque across the entire spectrometer range), traditional semiconductors have emissivity values around 0.7, and hence 250-300°C will be a lower temperature limit while maintaining better than1°C resolution. Today's narrow band gap semiconductor substrates such as **GaSb, InSb, InAs,** and **Ge** are fully absorbing/opaque over the NIR spectrometer range (880-1600nm) and present an ideal substrate for low-temperature monitoring with the kSA BandiT BB technique.

kSA Blackbody Temperature Measurement Technology: A Powerful Addition to the kSA BandiT System.

kSA blackbody temperature measurement technology is now integrated into kSA BandiT and represents the most advanced and flexible temperature monitoring system on the market today. In addition to band-edge based temperature, kSA BandiT includes broad-band pyrometry and the new kSA blackbody temperature monitoring technology (patent pending) developed by k-Space Associates. With this new development, kSA BandiT now addresses any and all temperature requirements and overcomes past limitations to the band edge-only approach to monitoring complex thin film deposition and epitaxial growth temperatures. kSA BandiT provides significant advances to traditional intensity-based temperature measurement such as Pyrometry and Emissivity Corrected Pyrometry (ECP), as follows:

- 10x higher S/N and temperature resolution
- Extended lower temperature range
- Higher accuracy and repeatability with in-situ band edge calibration
- Less sensitivity to stray radiation from filaments or plasma
- Less sensitivity to emissivity changes during sample multilayer thin film growth
- Less sensitivity to viewport coatings

	kSA Blackbody	*kSA Band Edge*	*kSA Broad Band Pyrometry*
Semi-insulating to lightly doped(<1e19) substrates	Advantage	Advantage	Advantage
Accuracy	Moderate	Advantage	Moderate
Resolution	Advantage	Moderate	Advantage
Reproducibility	Moderate	Advantage	Moderate
Highly doped (>1e19) substrates	Advantage	Advantage	Advantage
Thick, smaller band gap layers than substrate (>1.5um)	Advantage	Poor	Advantage
Low temperatures	>250 Degrees C (Advantage)	Room Temperature (Advantage)	Moderate
Viewport coating	Moderate	Advantage	Poor
High index multi-layer films	Advantage	Moderate	Poor
Emissivity changes	Advantage	Advantage	Poor

Advantage
Moderate
Poor

Table 1. Critical parameters that affect temperature measurement of today's semiconductor and thin film deposition processes. kSA BandiT now includes band edge, blackbody fitting, and broad band pyrometry for unmatched flexibility and performance with any material and application.

The above advantages, combined with newly designed, flexible mounting hardware, suggests kSA BandiT temperature measurement technology will quickly become an invaluable tool for monitoring most any process where end-device performance is reliant upon high resolution and repeatability temperature measurement. Please contact k-Space for more details or to arrange for an on-site demonstration to illustrate how blackbody temperature monitoring performance can add new insight into your process.

k-Space Associates, Inc.
Dexter, MI USA
Phone: 734-426-7977
Fax: 734-426-7955
E-mail: requestinfo@k-space.com
www.k-space.com

k-Space Associates, Inc., is a leading supplier to surface science and thin-film technology industries. Since 1992, we've delivered the most advanced thin-film characterization tools and software thanks to close collaboration with our worldwide customer base. We realize the best products are developed with our customers' input, so we're good listeners. For your real-time surface analysis, curvature/stress, temperature, deposition rate, or custom project, we look forward to helping you with your thin-film characterization needs.