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Example Provisional Patent Application (PPA)

In due course, this Provisional patent application (PPA) was re-written and filed as a utility (non-provisional) patent application in the U.S. Patent Office. The patent was eventually granted as **US Patent No. 8,282,273**

The following example is provided for educational purposes only in connection with **ELG's Practical Guide to PROVISIONAL PATENT APPLICATIONS for the Cost-Conscious Inventor**.

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BLACKBODY FITTING FOR TEMPERATURE DETERMINATION

In addition to band edge thermometry, this invention has the capability of performing non-linear least squares fitting of a blackbody radiation curve to acquired spectra. This allows a measurement of the temperature which is independent of the band edge method.

The spectral radiance is the fundamental measure of the amount of light emitted from a diffuse source that can reach a detector. It is defined as the emitted power per unit area of emitting surface, per unit solid angle, per unit wavelength. Figure 1 is a plot of the spectral radiance of a blackbody for several temperatures. Note that the curves never cross, and that the peak shifts to shorter wavelengths as the temperature increases.

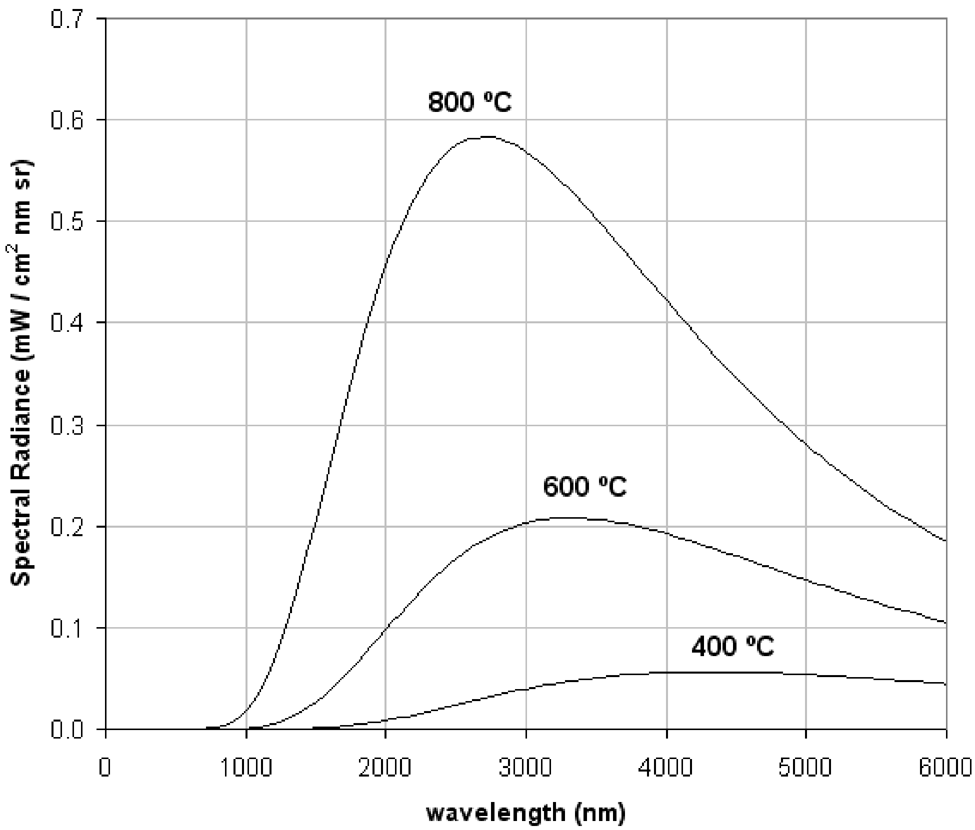


Figure 1: Spectral Radiance of a Blackbody

The wavelength of the peak radiance obeys Wien's displacement law:

$$\lambda_{\max} = \frac{b}{T}$$

where the constant b = 2.8978×10^6 nm K. Note that in the temperature range of interest for semiconductor film growth, the peak lies in the IR portion of the spectrum.

According to Planck's law, the spectral radiance I (□, T) of a blackbody at a given temperature is given by:

$$I(\lambda,T) = A\,\frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda k_B T}-1}$$

In fitting this equation to acquired spectra there are two adjustable parameters: the temperature T (which is in Kelvin), and the amplitude A. The amplitude is the product of the so-called "tooling factor" and the material's emissivity. The tooling factor incorporates system-dependent geometrical and sensitivity factors, and therefore must be determined empirically.

The amplitude can be determined by calibrating to a blackbody curve at a known temperature (e.g. from a band edge measurement or RHEED transition). In this case the temperature is held fixed, and the amplitude is allowed to vary to obtain the best fit. The tooling factor can in turn be determined by dividing the resulting amplitude by the material's emissivity. Once the tooling factor is known, a blackbody fit can then be performed in real-time during The invention data acquisition. In this case, the amplitude is held fixed, and the temperature is allowed to vary to obtain the best fit.

Procedure

1. First, the tooling factor must be determined. Begin by selecting Blackbody Calibration… from the Acquire menu of the software for implementing this invention. Also select the Real-time Blackbody chart from the View menu (see Figure 2). Within the Blackbody Calibration window, select the desired Spectra source from the pull-down menu. Set the Threshold, which specifies the minimum number of counts for performing a blackbody fit. Enter the calibration temperature (ºC), and the calibration sample's emissivity. The desired wavelength range over which to perform the blackbody fit must also be entered. Entering zeros will cause the software to automatically select the spectrometer's min and max wavelengths. The values can be locked using the check boxes. Alternatively, if one or both boxes are unchecked, the software will attempt to optimize the goodness of fit by successively reducing the range. A Goodness of Fit Threshold may be entered, which allows rejection of spectra with poor fits. Finally, enter a Blackbody Fit Tolerance. The fitting routine returns when the relative decrease in chi-squared is less than this tolerance value in one iteration (default is 0.001).

   Select Start. The software will determine the temperature by fitting a blackbody curve with the most recently saved tooling factor and emissivity to the source spectra in real-time. The Real-time chart displays the source data in blue and the resulting fit in red. Across the top it displays the temperature, emissivity and resulting tooling factor, and a goodness of fit statistic (i.e. the reduced chi-squared). Selecting Calibrate will fix the temperature and emissivity at the specified values and determine the corresponding tooling factor. If needed, the wavelength range can be adjusted. Every time Calibrate is selected, the wavelength range and resulting tooling factor are automatically saved. The Timeout setting allows the user to set the maximum time the calibration routine is permitted to run before timing out. This is relevant only if the fitting routine is taking an excessive amount of time to converge on a solution.

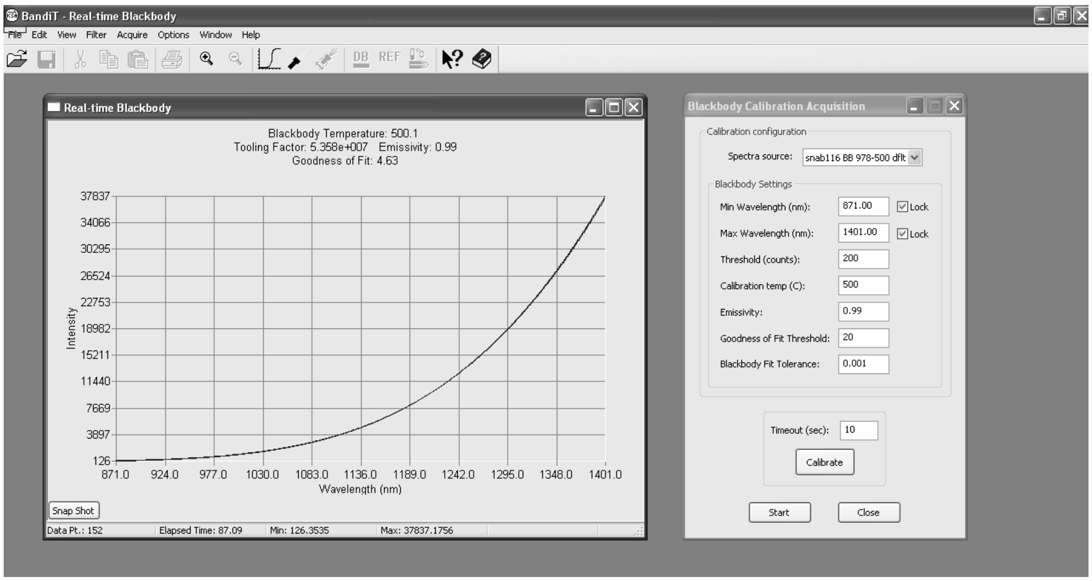


Figure 2: Blackbody Calibration Window & Real-Time Chart

2. Once the tooling factor is known, the spectra processing recipe must be set up. Select Temperature… from the Acquire menu. This will open the Temperature Acquisition window (see Figure 3). Within this window, select Advanced.

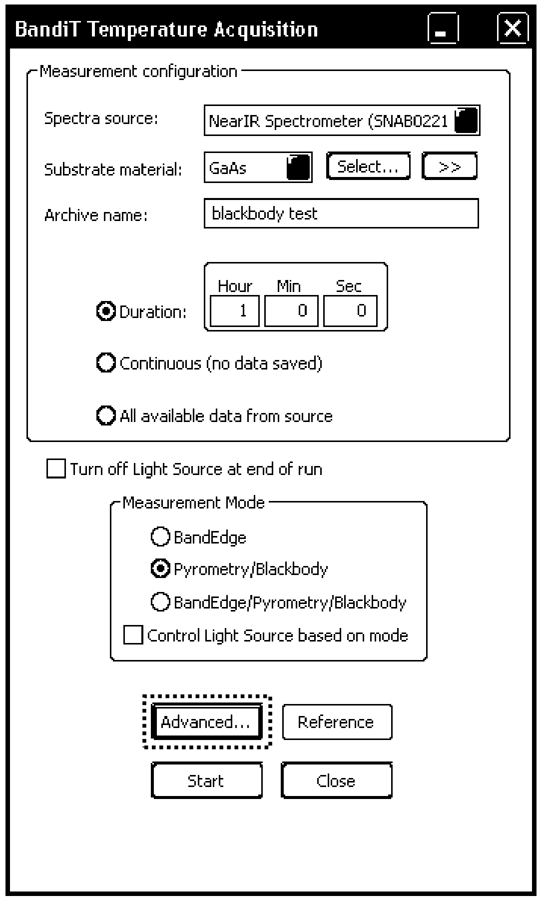


Figure 3: Temperature Acquisition Window

This will open the Advanced Acquisition Options window (see Figure 4). Within this window, select the Spectra Processing tab, and then select the Pre Processing sub-tab. Within this tab, the Enable box must be checked. The Noise floor setting specifies the number of counts below which the raw spectra will be ignored. The Raw Spectra Boxcar setting specifies the amount of smoothing to be applied to the raw spectra before processing.

Next select the Blackbody Fitting sub-tab. This will contain the tooling factor and the wavelength range, as well as the Goodness of Fit Threshold and Blackbody Fit Tolerance from the previous calibration procedure. The sample's emissivity must also be entered. Note that this is not necessarily the same as the emissivity used in the calibration procedure. This allows the user to perform the calibration on a sample which is different than the sample under test. The Blackbody Fit box must be checked. Also select the Lock Tooling Factor radio button. Finally, there is a Threshold setting, which specifies the minimum number of counts for performing a blackbody fit. In this example, any spectrum which has a maximum number of counts that is less than 200 will be ignored. When you are satisfied with all the settings, select OK. This will return you to the Temperature Acquisition window.

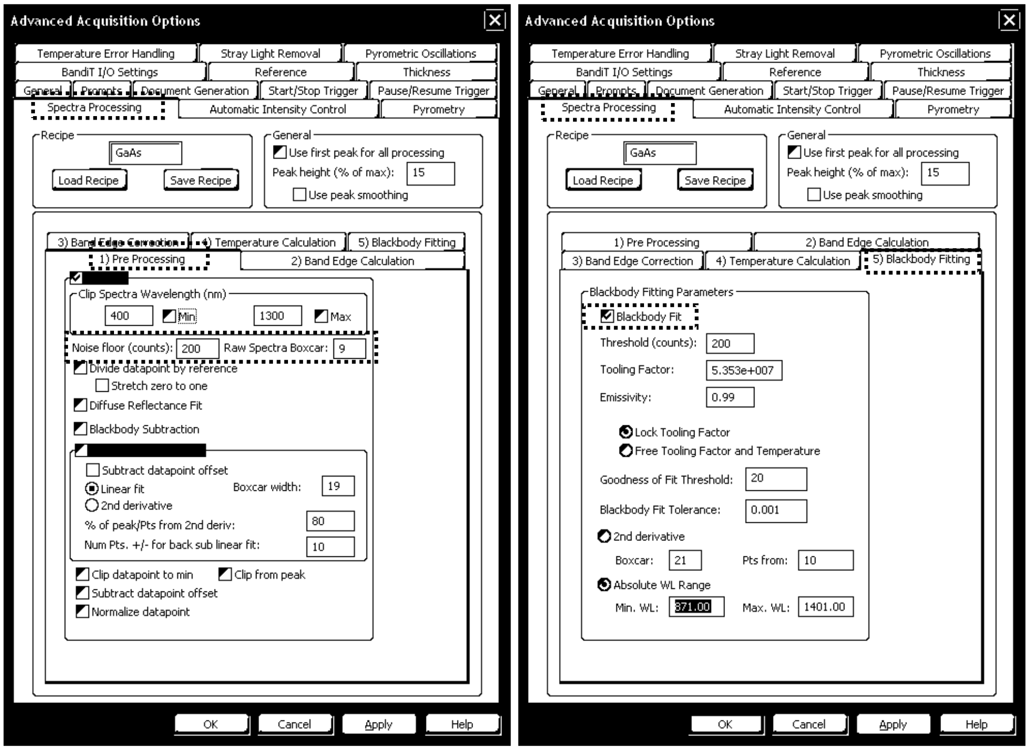


Figure 4: Advanced Acquisition Options

3. Now that the spectra processing recipe has been set up, acquisition can begin by selecting Start from within the invention Temperature Acquisition window. During data acquisition, in addition to the live spectrometer window, the user may view a number of Real-time Charts and Stats which provide useful information (see Figure 5). These can be accessed from the View menu. In this example, the following are displayed: Real-time Blackbody Chart which displays the raw data and the resulting fit, Real-time Stats (LED) which displays a user-selectable parameter (e.g. Blackbody Temperature), and Real-time Stats (Time) which plots a user-selectable parameter (e.g. Blackbody Temperature) versus time.

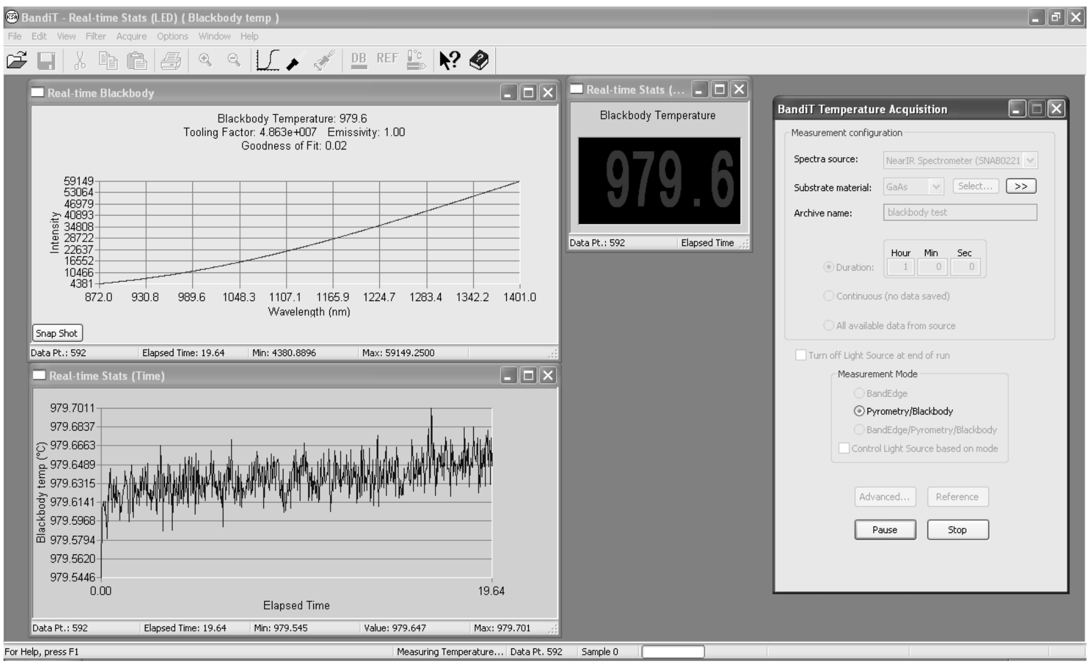


Figure 5: Real-Time Charts and Stats

Introduction & Motivation

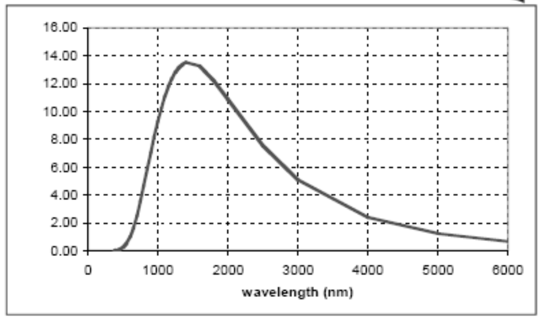


Figure 1: Blackbody emission of opaque sample at 2000K (1727 C)

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:

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

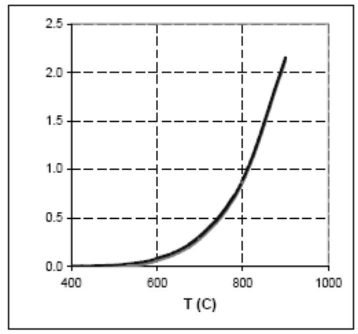


Figure 2: Emission intensity vs. wavelength at 1300nm

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').

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.

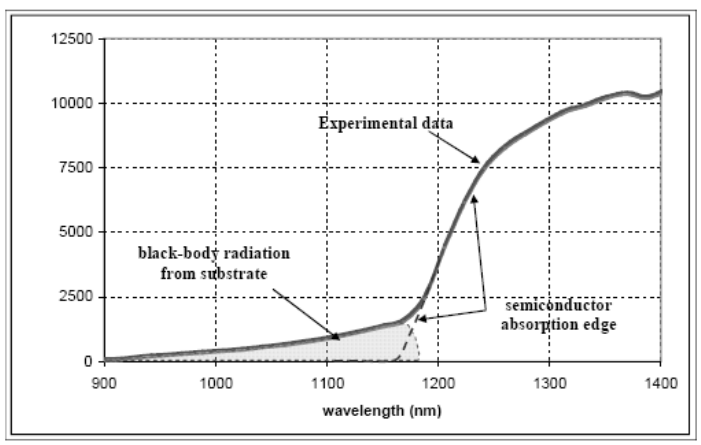


Figure 3: Blackbody emission from a semiconductor material follows Planck's Law: the valid portion of the curve is dependent upon temperature and band gap.

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.

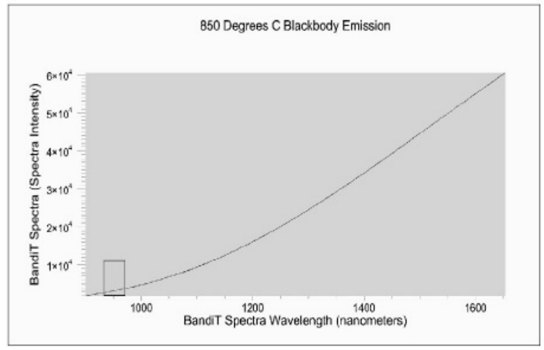


Figure 4: Standard pyrometry intensity collection window (950nm +/- 20nm).

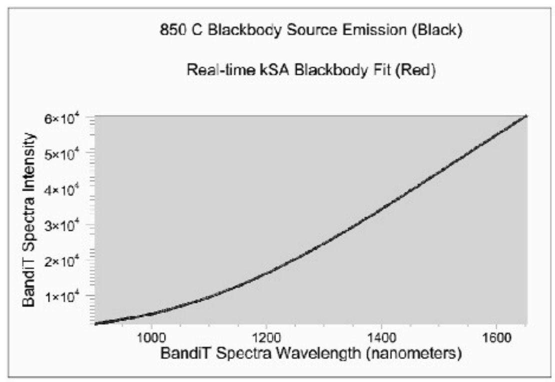


Figure 5: kSA BandiT collects intensity over a broad spectral range and fits Planck's equation in real time to determine temperature.

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.

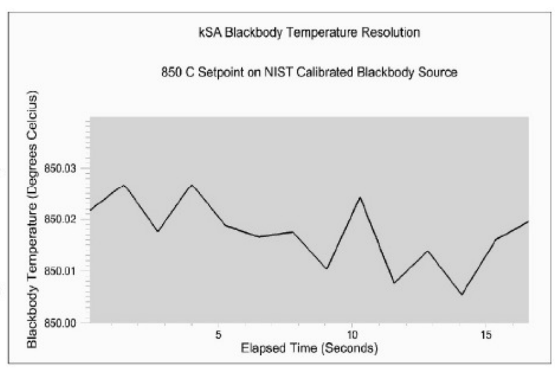


Figure 6. kSA blackbody temperature measurement yields better than 0.1°C resolution at 850°C.

kSA Blackbody Temperature Measurement During Growth

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.

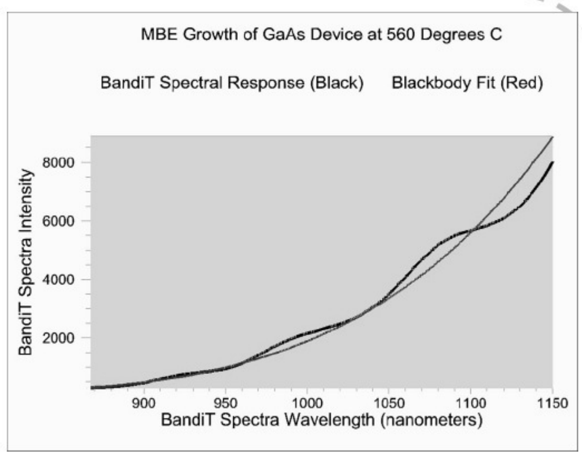
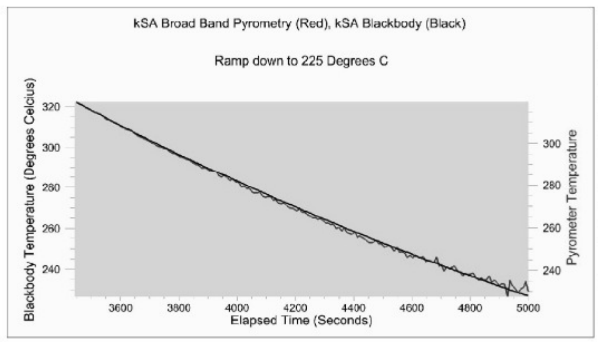


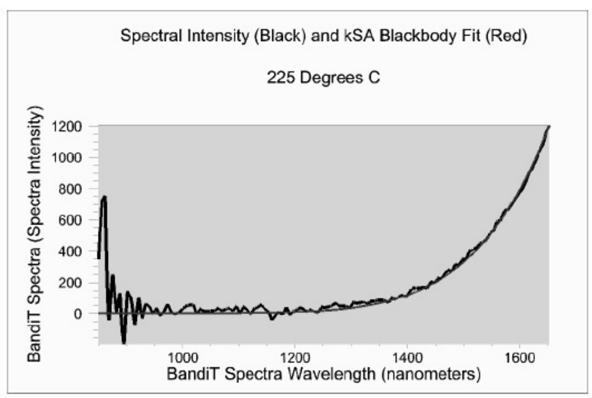
Figure 7: Spectral interference fringes propagate during heteroepitaxial growth. kSA BandiT fits through localized changes in emissivity and/or intensity, and hence the temperature remains stable.

Low Temperature Deposition

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 than 1°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.



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



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			
Accuracy			
Resolution			
Reproducibility			
Highly doped (>1e19) substrates			
Thick, smaller band gap layers than substrate (>1.5um)			
Low temperatures	>250 Degrees C	Room Temperature	
Viewport coating			
High index multi-layer films			
Emissivity changes			

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.

The foregoing invention has been described in accordance with the relevant legal standards, thus the description is exemplary rather than limiting in nature. Variations and modifications to the disclosed embodiment may become apparent to those skilled in the art and fall within the scope of the invention. Accordingly the scope of legal protection afforded this invention can only be determined by studying the following claims.

What is claimed is:

1. A method for measuring the temperature of a material using a block-body fitting technique substantially as shown and described herein.

2. An apparatus for measuring the temperature of a material using a block-body fitting technique substantially as shown and as described herein.