Technology Overview Note

Introduction and Motivation

Classical pyrometry, which measures thermally emitted radiation from a hot surface via a photo-detector and collection optics, is a very common in-situ temperature measurement technique for thin film deposition processes. However, as thin film layers are deposited, the emissivity of the surface changes due to the optical properties of the various layers and the resultant interference effects at the film interfaces. An emissivity change directly affects the heat loss from the surface of the wafer which in turn alters the balance in heat transfer, thus causing the surface temperature to change during film deposition. A classical pyrometer cannot account for this change in emissivity (*e*) since the emissivity value remains fixed during film growth, and thus may falsely record film temperatures. The standard pyrometry equation that relates the measured radiated power per area per solid angle per wavelength, *S*, to temperature, *T*, is given by:

$$\frac{1}{T} = \frac{1}{T_{cal}} - \frac{\lambda}{c_2} \ln\left[\frac{S}{S_{cal}} \frac{\varepsilon_{cal}}{\varepsilon}\right]$$

where *l* is the wavelength at which *S* is measured, c_2 is the second radiation constant, and S_{cal} is the calibration factor at a known calibration temperature T_{cal} and emissivity e_{cal}. To correct for the changing optical properties of the surface, the emissivity must be measured in real time, and this measured value used in temperature evaluation.

To understand how the kSA Emissivity Correcting Pyrometry (ECP) module determines the emissivity of the layers, we must consider that the radiant flux incident upon a surface can undergo transmission (T), reflection (R), and absorption (α). Conservation of energy requires that the sum of these must equal one, T + R + α = 1. Conservation of energy requires that the sum of these must equal one, T + R + α = 1.

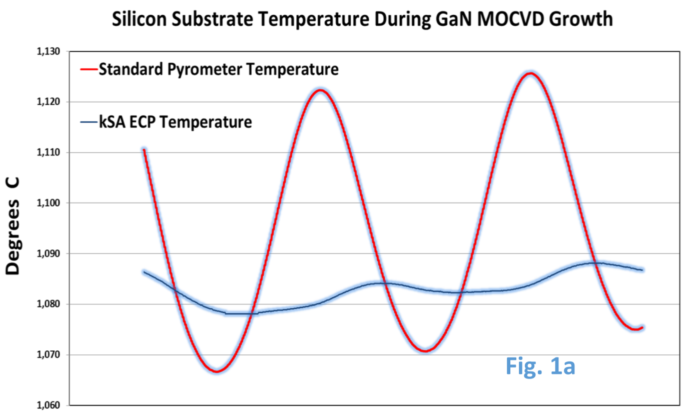
If the system is closed and at thermal equilibrium, conservation of energy also requires that emitted and absorbed fluxes are equal, i.e., the emissivity equals the absorptivity, or T + R + ε = 1. Furthermore, if we can assume that the sample is opaque in the spectral region of interest, i.e., the transmittance is equal to zero, then this equation can be simplified to R + ε = 1. This relationship shows that under certain conditions the sample emissivity can be determined by measuring the sample reflectance.

In practice, when measuring the film reflectance to determine the emissivity of the sample surface, three conditions must be valid for the thin-film growth. First, the transmittance equal to zero condition discussed above requires that the sample must be opaque, i.e.

ECP Module

- 950 nm centered radiation collection wavelength.
- 950 nm LED used for reflectivity and emissivity correction.
- Better than 1 °C resolution from 450 °C and higher.
- In-situ calibration via kSA Blackbody Calibration Module for highest accuracy and repeatability.
- ECP module can be integrated with existing and new kSA BandiT and ICE systems.
- Real-time reflectivity fitting for growth rate, thickness, and optical constants (n, k) also available.

fully absorbing, in the region of operation. As such, the pyrometer wavelength must be above the band gap of the substrate material at all temperatures of interest. If the substrate is transparent at this wavelength, the temperature of the metal backing maybe measured instead. Secondly, for the reflectivity measured to represent all light that does not enter the sample, the surface of the film must remain smooth and flat during the deposition. In this case, the incident light beam



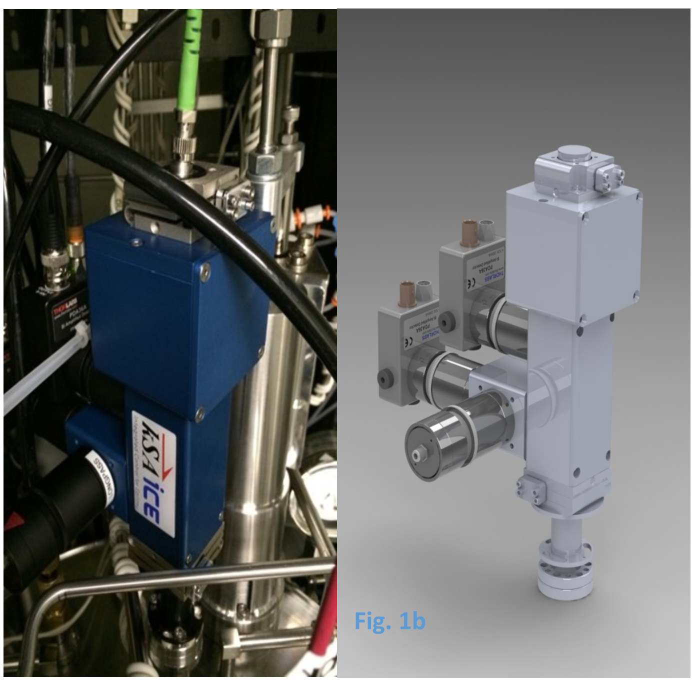


Figure 1: a) Temperature trace for GaN growth on Si comparing kSA ECP Module data (blue) and classical pyrometer data (red). b) Image of kSA ECP module integration with kSA ICE system and its installation on a D-180 MOCVD reactor.

used to measure the reflectance is secularly reflected with low scatter, hence it can be measured with a simple non-hemispherical) detector. The third condition is that the reflected light does not depend on the azimuthal angle of the sample, i.e., that sample rotation will not affect the magnitude of the reflected light. Given these three conditions we can assume that the ε = α = 1-R, and the pyrometry equation can be rewritten as

$$\frac{1}{T} = \frac{1}{T_{cal}} - \frac{\lambda}{c_2} \ln\left[\frac{S}{S_{cal}} \frac{(1 - R_{cal})}{(1 - R)} \right]$$

where R_{cal} is the reflectance at the calibrated temperature, and R is the reflectivity measured in real-time. Using this equation, the emissivity corrected pyrometer temperature is measured in real-time to obtain an accurate sample temperature during film growth and/or when the surface emissivity is changing.

kSA ECP Module Integration

The realization of the kSA ECP module by k-Space Associates, Inc. has leveraged our 15 years of experience with optical temperature monitoring and allows us to incorporate the latest advancements in photo-detector, collection optics, and LED technology. This makes the kSA ECP module one of the most robust, fast and reproducible systems available. Using a wavelength collection region centered at 950 nm and a corresponding LED emitting at this wavelength, the kSA ECP module operates over a temperature range of 450 - 1200 °C for most applications, with acquisition rates of less than 1 ms to handle even the highest sample rotation speeds. This module is great for measuring GaN on Si deposition, where it achieves 0.1 °C resolution at temperatures greater than 700 °C. In addition, the kSA ECP module can be in-situ calibrated via our patented Blackbody temperature measurement technique, to ensure both temperature accuracy and repeatability at any time.

kSA ICE Emissivity Correcting Pyrometry (ECP) Module

The kSA ECP module has been successfully integrated into existing kSA ICE and kSA BandiT systems for growth by both MOCVD and MBE. It uses the same software interface as our other monitoring tools for seamless integration into your process. The graph in Figure 1a shows a temperature trace for MOCVD growth of GaN on Silicon that was taken with a kSA ECP module integrated into a kSA ICE system (pictured in Figure 1b). The kSA ECP temperature is able to monitor the real surface temperature, whereas the conventional pyrometer shows temperature swings of over 50°C. Moreover, since kSA ICE is a multi-function tool, you can measure sample curvature, reflectivity, temperature, layer thickness, and growth rate all from one viewport. The kSA ECP Module has also been incorporated into our patented BandiT system (as shown in Figure 2) and was directly integrated into a production MBE reactor for precise temperature monitoring during multi-layer growth of As/P optical devices. The data in Figure 2a shows that the kSA ECP module achieved improved temperature stability and accuracy when compared with uncorrected pyrometry.

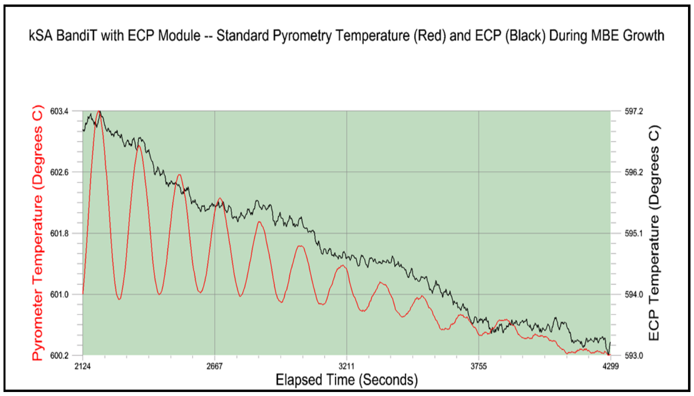


Figure 2: a) Temperature trace for MBE growth of AlGaAs on a GaAs substrate, comparing kSA ECP data and classical pyrometer data.

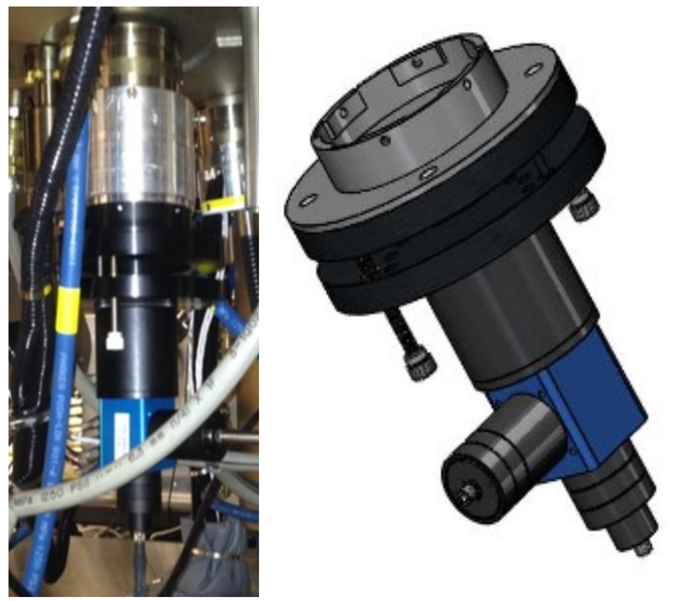
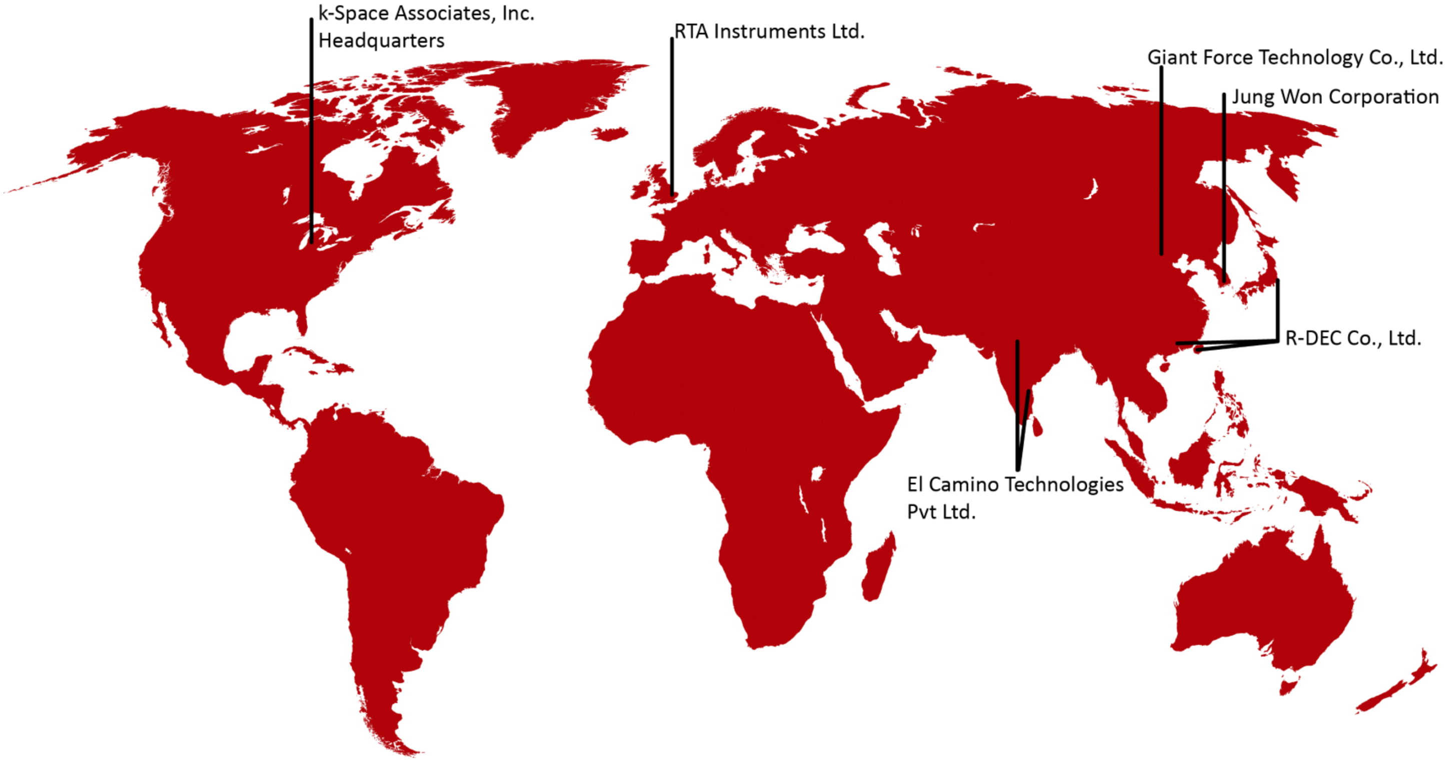


Figure 2: b) Image of the ECP module integration with kSA Bandit detector head, and its installation on a production MBE reactor.

The kSA ECP module can be an add-on to your current BandiT or ICE system, or built into your new kSA system. Please don't hesitate to contact us for further details!



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