

## *Model In-Situ 4000 Process Monitor User Manual*



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## Introduction

## Theory of Operation

### Pyrometry

Pyrometry is a method to calculate temperature by measurement of the electromagnetic radiation emitted by surfaces of opaque objects at finite temperatures. This effect is described by Planck's Law which describes the spectral radiance  $R(\lambda, T)$  as a function of wavelength and temperature:

$$R(\lambda, T) = \frac{2\epsilon hc^2}{\lambda^5} \cdot \left( e^{\frac{hc}{\lambda kT}} - 1 \right)^{-1}$$

Where  $\epsilon$  is the surface emissivity,  $h$  is Planck's constant,  $c$  is the speed of light,  $\lambda$  is the wavelength,  $T$  is the absolute temperature, and  $k$  is Boltzmann's constant. Thus if one knows the surface emissivity and has a well-calibrated radiometer, the surface temperature may be obtained. A black body is an ideal radiator and has  $\epsilon = 1$  for all temperatures and wavelengths, but real materials have emissivities less than one and may not have a constant value for all wavelengths. An example of a black body radiance curve for 700 °C is shown in Figure 1.

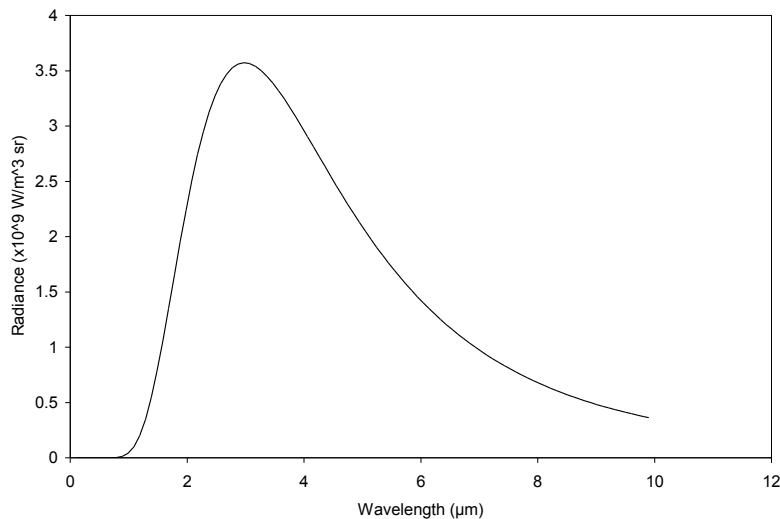


Figure 1 – Black Body Radiance Curve

Traditional pyrometry selects a fixed range of wavelengths and measures the emitted radiation intensity over that range. The resulting intensity vs. temperature relationship is exponential and allows a direct mapping of intensity to temperature. An example radiance curve vs. temperature at 950 nm is shown in Figure 2.

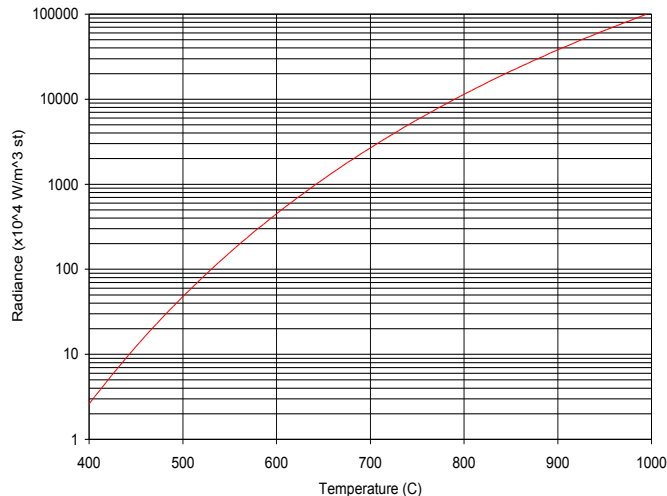


Figure 2 – Radiance vs. Temperature at 950 nm

Real surfaces have emissivity values less than 1 so the pyrometer instrument used to measure a surface temperature must have knowledge of the particular surface emissivity.

### Two-color Pyrometry

For surfaces where the emissivity is not known or the radiometer cannot be calibrated with absolute values, a technique known as “ratio” or “two-color” pyrometry may be used. Here, a single optical system is used to measure the radiance at two distinct wavelengths and the ratio of the radiant intensities is calculated. Assuming that the emissivity is the same for the two wavelengths (i.e. a “grey body”) the ratio of the radiance equation above becomes:

$$\frac{R(\lambda_1, T)}{R(\lambda_2, T)} = \frac{\lambda_2^5}{\lambda_1^5} \cdot \frac{\left( e^{\frac{-hc}{\lambda_1 kT}} - 1 \right)}{\left( e^{\frac{-hc}{\lambda_2 kT}} - 1 \right)}$$

and the ratio is independent of emissivity and the absolute radiometric gain. Thus the temperature may be computed from knowledge of only the measurement wavelengths and the intensity ratio. An example curve of radiometric ratio vs. temperature is shown below in Figure 3 for the wavelengths of 950 nm and 850 nm.

This feature of ratio pyrometry is very convenient in correcting errors, which affect both wavelengths equally such as optical misalignment, viewport window coating, or an unknown emissivity.

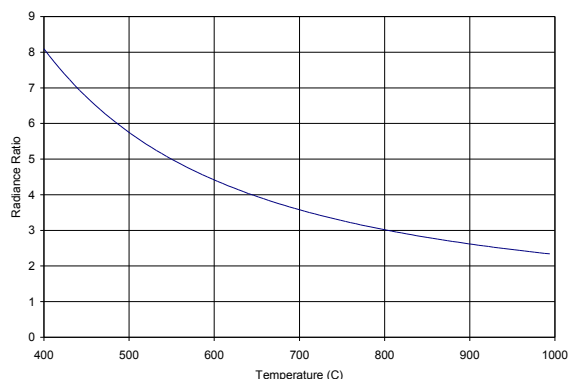


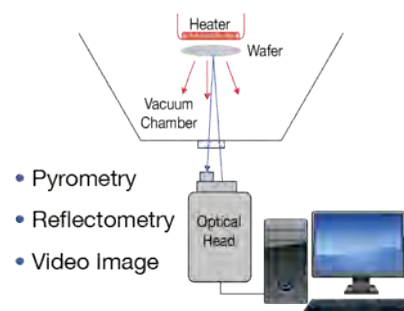
Figure 3 – Ratio of Radiance vs. Temperature for 950 and 850 nm Wavelengths

The intensity ratio vs. substrate temperature will differ for varying substrate materials, so the In-Situ 4000 system allows the flexibility of a look-up table (See Appendix – LUT section) to translate from intensity ratio to reported temperature. This look-up table can be changed for different substrates, or updated to compensate for any calibration errors or instrument drift. The ratio pyrometry feature of the In-Situ 4000 provides the user with a repeatable day-to-day calibration, which is independent of viewport coating effects.

## Reflectance

In addition to accurate pyrometry, the reflectometer feature of the In-Situ 4000 Process Monitor measures specular reflectance at two wavelengths: 950 nm and 470 nm.

The reflectometer uses two LEDs housed in the optical head to illuminate the wafer through the vacuum viewport window and detects the light with the same optical system as the pyrometer. Thus the system needs only a single, normal incidence viewport that is provided in many vacuum systems. The viewport must be large enough to allow room for both the illumination light to enter and the reflected and pyrometric radiated light to exit the chamber. The In-Situ 4000 requires a 2.75 inch Conflat viewport or larger to accomplish this measurement. Another requirement is that the viewport window is located at normal incidence to the substrate so that the illumination beam is specularly reflected back to the instrument. This places some limits on the substrate holders, which need to maintain normal incidence alignment during use and especially during wafer rotation. The In-Situ 4000 system has special software features, which can allow the measurement to function well even if the substrate tilts strongly during wafer rotation. (See Wobble Filter Chapter)



Reflectance is used in this instrument for two reasons:

1. When single or multiple layer films are deposited, optical interference will alter the emissivity of the substrate as a function of time and the single color pyrometry will be in error. Measurement of specular reflectance at the same wavelength as the single color pyrometry will allow the calculation of emissivity through the relation  $\epsilon = 1 - R$  which is based on conservation of energy considerations and Kirchhoff's Law. Note that this relation is valid only for opaque substrates.

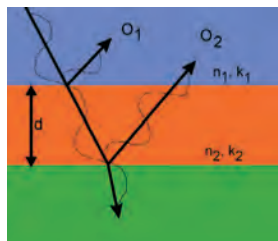


Figure 4

**Principle of Thin Film Interference**

$$2n_2 = m\lambda \text{ for maximum reflectance}$$

$$2n_2 = (m + \frac{1}{2}) \lambda \text{ for minimum reflectance}$$
 $n$  = index of refraction

 $k$  = extinction coefficient

 $d$  = layer thickness

Reflectometry is obtained in real-time during deposition so that films that have differing index of refraction from the substrate produce reflectance oscillations in time. These reflectance oscillations can be analyzed in real-time to provide both film thickness and film index of refraction. The In-Situ 4000 has powerful analysis algorithms, which can provide accurate growth rate, thickness, and index information. This valuable information can even be fed back to the growth system controller to achieve layer thickness precision improvements over traditional open-loop timed deposition control. The best growth rate and index of refraction measurements are obtained with films of at least  $\lambda/4$  in thickness where  $\lambda$  is the reflectometer measurement wavelength (i.e. 950 nm or 470 nm). See Growth Rate Fitter Chapter.

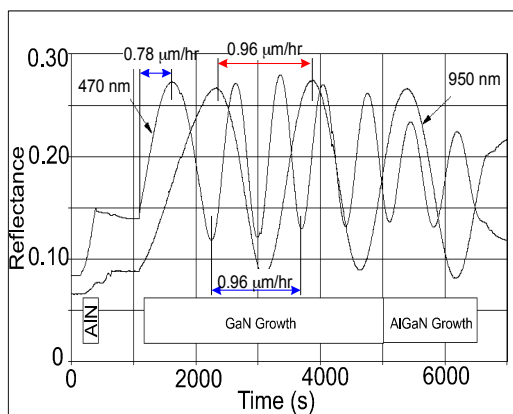


Figure 5 – Growth Rate Measurement during GaN/AlGaIn Growth using Two Wavelengths (950 nm and 470 nm)

- The specular reflectance of a thin film may change with deposition of the film due to multiple layer interference if the film has an index of refraction that is different from the underlying material. If the index of refraction of the depositing film is known (at elevated temperature) then the film thickness and growth rate may be calculated from the periodic undulations in specular reflectance with time.

### Emissivity Compensated Pyrometry

The problem of unknown or shifting emissivity is solved using information from the accompanying reflectometer system. Under the conditions of an opaque substrate, a perfectly specular substrate front surface, and perfect uniformity of the deposited films, the emissivity may be measured via reflectometry at the same wavelength as pyrometry. The relation linking emissivity,  $\epsilon$ , and reflectometry,  $R$ , under these conditions is:  $\epsilon = 1 - R$ . The In-Situ 4000 provides a 950 nm reflectometer which is matched to the 950 nm pyrometry system thus allowing this “emissivity compensation” to provide an emissivity independent temperature measurement. Thus, if the film being deposited has a different optical absorption at 950 nm, and/or has a different index of refraction as the substrate producing interference



effects, reflectometry will observe these changes and the software will correct the error in the temperature calculation. The success of this technique depends upon how closely the material system conforms to the assumptions listed above, namely substrate opacity, surface specularity (smoothness), and film uniformity. If the substrate is not sufficiently opaque or the surface is rough and scatters significant amount of light, the  $\varepsilon = 1 - R$  relation is no longer true. If the deposited film is not uniform, then the reflectance measurement (made at a single point on the substrate) may not be well correlated to the pyrometry measurement (made over a larger area of the substrate).

The three techniques of single-color pyrometry, ratio pyrometry, and specular reflectance are combined in the In-Situ 4000 temperature instrument. The single color pyrometry temperature measurement is the preferred method because it has better noise performance than the ratio method. The 950 nm reflectometry allows calculation of the varying 950 nm emissivity resulting in emissivity compensated pyrometry. Since there are instrumental and alignment errors in measuring absolute radiometry, the single color method actually calculates temperature based on previously measured radiation at a known temperature. Future calculations of temperature are made relative to the single reference measurement. In the In-Situ 4000, the reference calibration may be made using the ratio method, or through some other method such as oxide desorption or a eutectic temperature measurement. (See Calibration of the Temperature Instrument chapter)

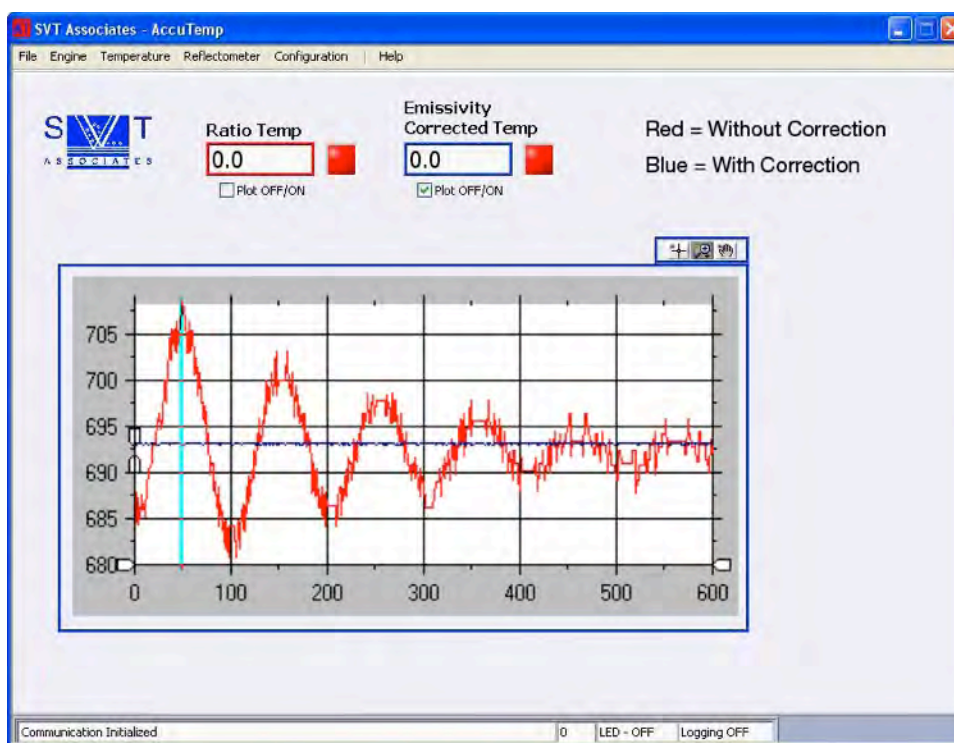


Figure 6 – Temperature Measurement during GaN Growth using Emissivity Compensation

### Problems with Pyrometry of Semiconductors

Pyrometry is a well-established measurement technique and is successfully used in many applications. It has one main feature that makes it attractive for substrate temperature measurement during MBE or MOCVD: it is a non-contact and vacuum compatible temperature sensing method. However as those who have used pyrometry for semiconductor applications know, this technique can be fraught with problems, which greatly limit its usefulness.

SVT Associates has recognized the problems with pyrometry of semiconductors and has designed the In-Situ 4000 specifically to solve many of the problems preventing pyrometry from being a useful tool for both MBE and MOCVD processes. This system combines traditional pyrometry with specular reflectometry to provide a single instrument to monitor both substrate temperature and film thickness in real time. Listed below are some of the problems and how the In-Situ 4000 overcomes them.

1. **Substrate transparency.** Semiconductors by nature are partially transparent for wavelengths below the band gap that is usually in the infrared portion of the spectrum. This transparency causes two severe limitations in pyrometric measurements: low substrate emissivity and optical interference from other hot elements in the chamber.

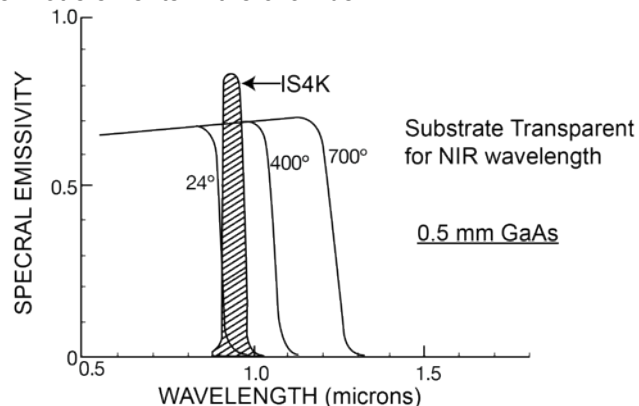


Figure 7 – Substrate Transparency of GaAs requires small spectral detection range and limits Temperature Measurement to 370 °C @ 950 nm

The problem of low emissivity and substrate transparency at infrared wavelengths is addressed by careful selection of the pyrometry wavelength. The In-Situ 4000 performs single wavelength pyrometry at 950 nm, which is short enough to ensure that the substrate is opaque, and long enough to ensure a measurable optical radiation at growth temperatures. Ensuring substrate opacity is a key element in addressing several of the previously listed difficulties. An opaque substrate prevents radiation from a filament heater from being transmitted through to the pyrometer. It also prevents other radiation sources in the chamber (effusion cells, ion gauge filaments, etc.) from scattering their light from the rough back side of the substrate into the pyrometer. Since optical absorption and black-body radiation are closely coupled, substrate opacity ensures that the emissivity of the substrate is high enough to provide a measurable signal. Typical substrates such as silicon, GaAs and InP are sufficiently opaque at 950 nm for substrate temperatures typical of epitaxial growth. The condition of substrate opacity may break down for some low temperature processes where the band edge may shift close enough to 950 nm to cause some problems. Therefore, the user must be careful to ensure opacity of the substrate at the temperatures of interest.

2. **Band gap shifts.** The band gap of a semiconductor substrate is a strong function of temperature and so the basic assumption of constant emissivity made by standard pyrometers is not valid. (See Band Gap based AccuTemp in the Appendix) An example of  $\text{In}_x\text{Ga}_{1-x}\text{N}/\text{Al}_x\text{Ga}_{1-x}\text{N}$  is shown in Figure 8. Using emissivity corrected pyrometer allows compensation for emissivity layers.

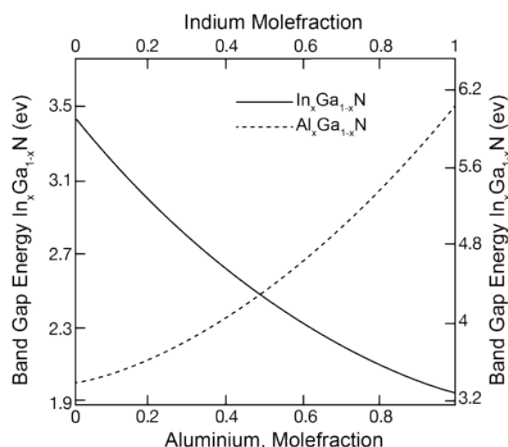








Figure 8 – Dependence of band gap on Al and In mole fractions

3. **Viewport coating.** Standard pyrometry computes temperature from the intensity of emitted radiation. If the viewport window through which the pyrometer measures the radiation becomes coated over time, the pyrometer temperature calibration will drift accordingly. This problem is addressed in the In-Situ 4000 through the use of “two-color” or “ratio” pyrometry, which measures optical radiation at two wavelengths and takes the ratio of the measured intensities. If the film coating of the viewport is spectrally neutral then the temperature may still be calculated since these errors affect both channels equally. Since many of the viewport coating problems deal with “metallic” type films (e.g. Ga, In, As), these films attenuate the light equally between the two wavelengths; the ratio calculation is still valid. If the viewport becomes coated with a dielectric film causing interference effects, then the ratio measurement becomes imbalanced and may not be valid.
4. **Alignment and optical obscuration errors.** This problem is similar to viewport coating in that there are errors introduced into the collection of radiated intensity by misalignment of the optics to the viewport window or other obscuration problems.
5. **Pickup of stray light.** Any hot surface in the chamber can radiate light. If that light makes its way into the pyrometer, the pyrometer will not be able to distinguish between “black body” radiation of the substrate itself and that of the stray light. Thus the stray light introduces an error into the measurement usually causing a higher than actual reading.
6. **Multilayer interference effects.** When thin films having different index of refraction from the substrate are deposited, the resulting interference effects cause the radiated light to rise and fall with the film thickness even if the actual temperature is constant. This causes temperature measurement errors during film growth and can cause actual temperature fluctuations due to non-constant radiative cooling of the substrate.

## Unpacking and Installation

### Unpacking

The In-Situ 4000 Process Monitor consists of the following components:

Part Number	Description	Image
5038705	Optical sensing head	
5034399	Wall mount power supply or a dedicated rack-mount controller	
5022756	Computer interface cable	
5035078	Video monitor	
500834	Video cable	
	Software application DVD	
	User manual	
5036126	Optional remote illuminator	

Unpack all components and remove any protective wrapping. Please save the shipping material for future use if the unit must be returned to SVT Associates.



**Caution:** The optical head is constructed using a strong outer enclosure and is quite rugged. However it is a precise optical instrument and must be treated with care. Dropping the instrument on the floor or other rough treatment may cause damage, which is not covered under warranty.

## Mounting

Typically you can use the flange mount provided by SVT Associates to mount the In-Situ 4000 unit. However, the optical head has two standard tripod mounting holes located on the bottom of the unit. Either, or both, of these holes may be used to mount the optical head on a tripod or other mounting bracket. These holes are machined with 1/4-20 inch threads, which are also compatible with standard opto-mechanical mounting hardware from suppliers of optical hardware.

Mechanical stability is very important in using this system, so ensure that the optical head is rigidly mounted and will not move or vibrate during the entire intended use of the product. Also, the instrument requires a precise pointing alignment to the wafer under measurement so the mounting system should include adjustment capability for precise pointing of the instrument.

Tri Pod Mounting Holes

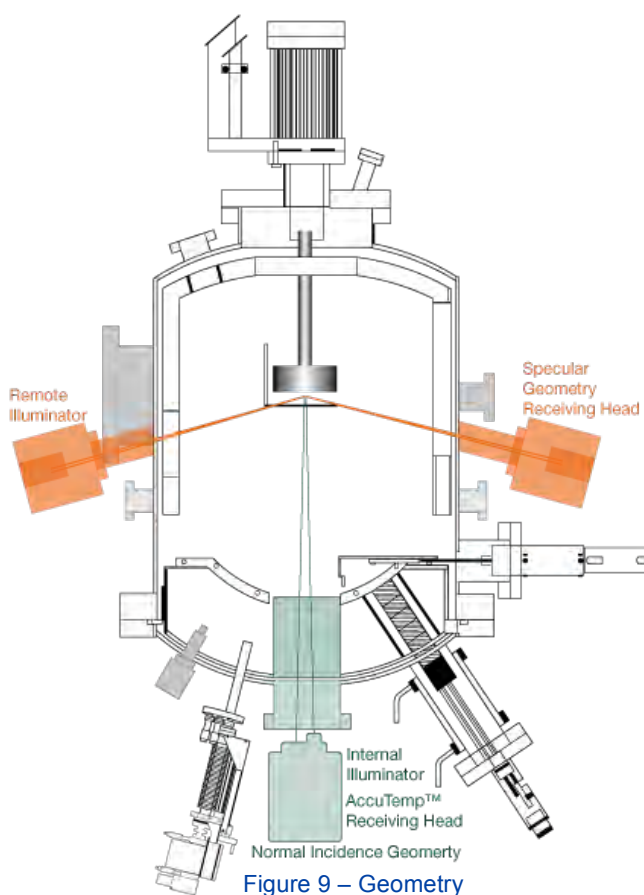


Figure 9 – Geometry

The optical head should be mounted within 4 inches of the vacuum viewport window for best results. Mounting the instrument close to the window reduces the LED illuminator's light from being reflected back directly into the instrument.

The vacuum viewport flanges compatible with this instrument are 2.75" Conflat™ Flange or larger. Ensure that neither the LED illuminators on the front of the optical head, nor the objective lens are blocked from viewing the substrate.

The instrument is designed to view the substrate from a normal or specular incidence so that the light from the illuminator is specularly reflected back toward the instrument. If this geometry cannot be achieved, then the reflectometry portion of the instrument will not produce useful information and the pyrometry performance will be limited by no longer allowing emissivity measurement. If the user requires a non-normal incidence, a remote illuminator may be purchased which will provide a specular reflection of the LED light into the optical head.



### Mounting Using SVT Associates' Flange

- Locate the In-Situ 4000 Flange Mount. The mount should be fully assembled.
- There are four 1/4-20 socket head set screws around the circumference of the mount. Using a 7/32 Allen wrench back the set screws out until they clear the inner diameter of the mount. (See Figure 10) The flange mount has an ID tolerance of approximately .015 inches. Nothing, such as bolt heads or washers, may be protruding beyond the flange! Use socket head screws if necessary on your flange.
- Install the mount over the flange with the platform down. Tighten all four set screws equally until the mount is firmly attached to the flange.
- Looking at the mount find the four 8-32 screws that attach the platform to the side gussets. Note that the gussets are slotted. These slots allow the platform to be moved vertically and also to be tilted fore and aft.
- The optical head is attached to the platform through two slotted cutouts. These slots allow the optical head to be moved left and right and also allow for a rotational adjustment. (See Figure 11)
- Locate the optical head and mount it to the platform using two 1/4-20 hex head bolts.
- Mount the IS4K head using provided flange mount to the chamber viewport. Use all four setscrews of the flange mount to hold it in place. Make sure both 1/4-20 screws on the bottom are fastened to hold the optical head on the platform.
- Make sure the objective lens is approximately centered in the mechanical holder to start. See Optical Head Alignment section on page 18 of this manual for detailed information.



Figure 10



Figure 11

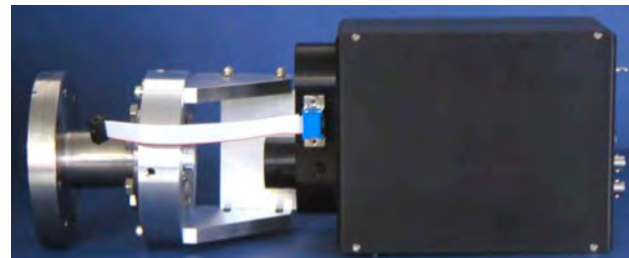


Figure 12

## Electrical Connections

The In-Situ 4000 optical head provides a panel of connectors on the rear of the unit for connection of electrical cables. The connectors are from left to right: video signal, sync signal, computer interface, and power supply. (See Figure 13)

Three cables (supplied) are needed for normal operation:

1. Power supply cable 5034399
2. Computer serial interface cable 5022756
3. Video signal cable 5005834

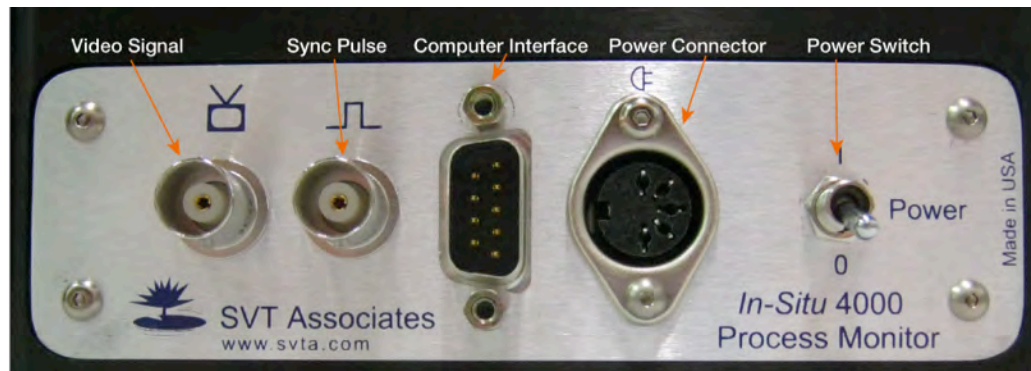


Figure 13 – Rear view of the optical head showing connector panel.

Connect one end of the serial cable to the 9-pin Computer Interface connector on the rear of the optical head. Connect the other end of the serial cable to an available serial port (RS232) on your computer. Be sure to fully tighten the connector screws on both ends to ensure a reliable data connection.

Locate the video monitor and set it at a convenient location to the optical head. Connect the coaxial video cable from the BNC video signal connector on the rear of the optical head to the video input connector on the video monitor. Plug the video monitor power cord into the wall power outlet.

Make sure the power switch on the optical head is in the off position, then plug the round power cable connector into the power connector of the optical head and plug the power supply into the wall power outlet. A dedicated rack-mount controller might be provided.

The optical head may now be powered on and is ready for use.

## Other Recommended Usage Notes

### Window Glare Reduction

The LEDs that direct light at the substrate for the reflectometry measurement can also generate unwanted glare from the viewport window through which the instrument is viewing the substrate. If the optical head is separated from the vacuum viewport window by more than 100 mm, there will be a reflection from that window back into the reflectometer. This glare can be accommodated in the reflectance calibration, however the glare signal is often larger than the reflectance from the substrate under measurement and has the effect of significantly reducing the signal quality (i.e. more noise) and making the instrument more sensitive to misalignment errors and mechanical motion. Use of the optical head with less than 100 mm of distance to the viewport is highly recommended.

### Use With Small Viewports

The optical head is designed to view through vacuum viewports with at least a 33 mm diameter window, which is found, for example, on a standard 2¼ inch Conflat Pyrex viewport flange. Smaller viewport windows are not recommended because either the outgoing LED light or the returning reflected light, or the black-body radiated light will be obstructed by the window frame and the measurement results may be incorrect. Contact SVT Associates for further information on using smaller viewports.

### Use With Transparent Substrates

The In-Situ 4000 is designed for use with substrates that are optically opaque at 470, 850, and 950 nm. Care must be exercised when attempting to use the instrument with transparent or partially transparent semiconductor substrates. Substrate transparency causes the following problems:

1. The radiated light from a substrate heater located behind the substrate will be transmitted through the substrate and enter the radiometer. The radiometer cannot distinguish between radiation from the substrate and that transmitted through the substrate and a pyrometry measurement error will result. One solution to this problem is to coat the backside of the substrate with a sufficiently opaque metal coating.
1. Semiconductor substrates have varying transparency with temperature. Many semiconductor substrates are partially transparent at 850 and 950 nm at low temperatures. At higher temperatures, typically the band gap shifts to longer wavelengths and the substrate becomes acceptably opaque. The wavelengths used in the In-Situ 4000 were chosen to be opaque for silicon, GaAs, and InP substrates at elevated temperatures. Silicon, for example, is partially transparent at 950 nm below about 550 °C and so pyrometry measurements may be adversely affected at lower temperatures. Depending on doping levels, GaAs substrates can be partially transparent up to 600 °C. When the substrate is transparent, the effective emissivity will be low, yet the emissivity measurement will not be correct since the emissivity calculation is based upon the assumption of opaque substrates. (See Figure 7)
2. If a substrate is transparent, the backside texture of the substrate is visible to the pyrometric radiometer. A non-polished back surface will then scatter stray light in the deposition chamber into the optical head and may cause an errant reading. This may be evident when using vacuum instruments with glowing filaments like ion gauges, mass spectrometers, etc. Also, radiation from electron beam or effusion sources may also be scattered into the optical head and affect the pyrometry adversely. Solutions to this problem may be to use substrates polished on both sides, or ensuring pyrometry is performed at high enough temperatures where the semiconductor substrate is sufficiently opaque.
3. If the transparent wafer is optically polished on both sides, then the normal incidence specular reflectance must be known prior to loading in the vacuum chamber. This is because there are now two surfaces, which reflect light back to the reflectometer, and the back surface, if coated with an opaque film, will have a much different reflectance than that determined by the substrate index of refraction.



### Focusing Tips

The optical head has two different detection branches for detecting both pyrometric radiometry and reflectometry. Both of these systems focus at the same distance, however there are two different cases one may choose to optimize focus: 1) at the substrate or 2) on the LED illuminators which is twice the substrate distance. Focusing at the substrate creates the smallest possible measurement area for pyrometry, however the LED image is out of focus and “blooms” to a relatively large size. This large size may cause the reflectometer to become more sensitive to substrate tilt errors. Tilt error effects are minimized when the system is focused at the LEDs to make the LED image as small as possible. This method causes the pyrometry sensor to be defocused and will sample an area larger than the 2-degree field obtained when focusing at the substrate. (See Optical Head Alignment Chapter)



Optimize Focus – Substrate



Optimize Focus – LED

Thus for large area substrates the best performance is obtained by focusing at the LEDs, because the larger than normal pyrometry sensing area will still be contained within a large diameter substrate. However, for small area substrates the best performance will likely occur when focusing at the substrate to ensure the pyrometry is measured within the boundaries of the substrate surface.

### Film Thickness Non-Uniformity

The computation of emissivity based on the measurement of reflectance is made based on the assumption of uniform film properties across the substrate. If the film thickness, for example, varies substantially across the substrate, then the pyrometry measurement and the emissivity measurement may no longer be correlated since they may be measured at different places on the substrate and hence difference thicknesses. If that is the case then the temperature compensation may be compromised and a temperature error may result. Substrate rotation or other means of ensuring film uniformity is strongly recommended.

## Optical Head Alignment

The optical head must be positioned so that the LED illuminator and the objective lens on the front of the instrument have a clear and unobstructed view of the substrate under measurement. In addition, the optical head must be oriented perpendicular to the substrate so that the reflected light from the illuminator is directed back into the objective lens. If this alignment cannot be achieved, then the reflectance measurement is not possible and the pyrometry performance is compromised.

Alignment of the optical head using the In-Situ 4000 internal light source:

With the optical head power on, start the software application and turn on the LED illuminator.

Point the optical head so you can view the substrate in the video monitor. Additional illumination applied to the substrate may be required, for example by a flashlight shining through a spare viewport or the glow from an ionization gauge.

Focus the image on the video monitor by loosening the objective lens set screw and sliding the lens in and out to obtain a focused image of the substrate. When trying to view a large polished substrate with no features to observe in the image, you may need to perform a focus operation before the substrate is in place and instead focus the image when viewing the substrate heater. Ensure that the focus adjustment set screw is secure before continuing.



Once the substrate area is centered in the video image, the reflection of the LED illuminator must be visible in the image. Perform additional tilt and translation adjustments of the optical head and/or the substrate to achieve a normal incidence reflection. Center the image of the LEDs in the video image.

**Note:** The LEDs used to illuminate the substrate are quite bright and may saturate the video image producing unusual patterns on the screen. Be assured this saturation will not damage the video camera electronics and that this image is normal.



Figure 14

Once aligned, the instrument is prepared for temperature and reflectance measurement.

There are two different fields of view for the two different types of measurements. The standard pyrometer detectors have a two degree field of view (Figure 15 orange color) whereas the reflectometer detectors have a 3.6 degree field of view (Figure 15 blue color). The video image views the reflectometer view so the dark boundary outside of the central video image corresponds to the limits of the reflectometer field. The pyrometer field is approximately 55% of the reflectometer and is centered on the video image. **Note:** The inset in Figure 15 shows the alignment when only a quarter of a wafer is used.



Figure 15

**Note:** there is a fourth electrical connector present on the rear panel which supplies a TTL compatible sync pulse signal for synchronization of external, non-normal incidence illuminators.

If you ordered the optional external illuminator follow instructions to install it. Locate the external illuminator and the external illuminator cable. Mount the external illuminator to a 2.75" viewport. The illuminator has one screw to clamp it to the viewport. Using the external illuminator ribbon cable attach the illuminator to the In-Situ 4000. The DBM9 on the cable attaches to the DBM 9 on the front of the In-Situ 4000, and the 10-pin ribbon connector goes to the illuminator. The illuminator connector is keyed for proper electrical connection.



Figure 16

## Software

### Software Installation

The software is installed under Windows (XP) or Windows 7 operating system by executing the program "Setup.exe" on the supplied DVD. Follow the directions given by the installation program. The DVD provides calibration information; please use this calibration information when prompted by the installation program.

At this point the software installation has the factory calibration values installed on the computer hard disk and will remember these values each time the RoboMBE program is executed.

**Note:** This procedure to load the factory calibration values must be performed after each installation of the RoboMBE program.

**Note:** The first time the application is run, the serial RS232 communication port, or COM Port, used by the computer must be assigned and the communication values specified. The correct values to use are:

Data Rate	9600 bps	
Parity	None	(See Data Acquisition Setup)
Stop Bits	1	

### Menus

Below is an overview of the software menus with a short description.

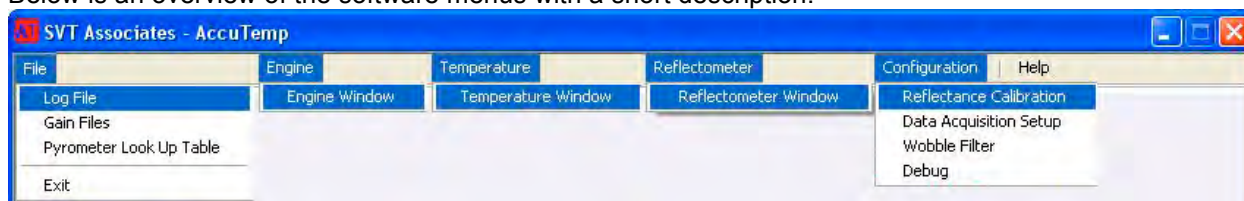


Figure 17

#### File Menu

Log File – turn file logging on or off. Page 21

Gain Files – select and change the Gain settings. Page 24

Pyrometer Look Up Table – select the temperature LUT calibration file. Page 26

Exit – exits the software application

#### Engine Menu

Engine Window – displays measurement values and operates the In-Situ 4000 unit. Page 27

#### Temperature Menu

Temperature Window – view temperature signals. Page 28

#### Reflectometer Menu

Reflectometer Window – view reflectance signals and calculate growth rate. Page 29

#### Configuration Menu

Reflectance Calibration – calibrate reflectometer intensity signals. Page 31

Data Acquisition Setup – set up COM port settings and calibrate geometry factor. Page 33

Wobble Filter – correct for wafer tilt during rotation. Page 35

Debug – service mode of the In-Situ 4000

[Help Menu](#)

View help manual

## Start Up Screen

When you first start up the software you will see the Temperature window.

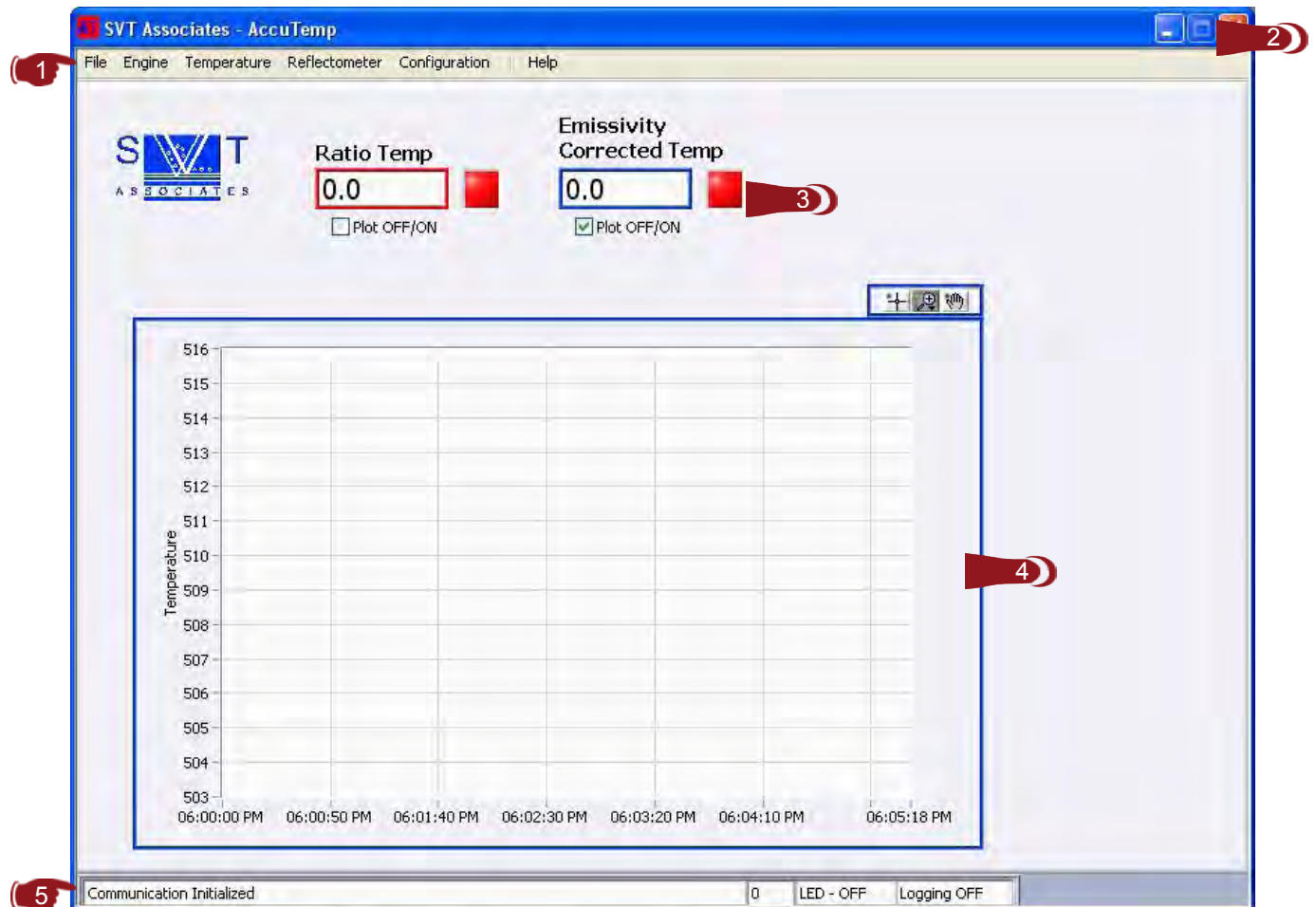


Figure 18 – Temperature Window

1. Main Menu Navigation
2. Minimize or close window
3. Shows signal value
4. Main charting area
5. Status Bar – shows if communication has been initialized, number of data packages via the COM port, whether the LED illuminators on the optical head are ON or OFF, and if Logging is ON or OFF.

Before using this instrument you need to perform other setup steps, see the section on Data Acquisition Setup.

## Managing Graphs and Windows

Each of the instrument windows may display a strip chart graph showing the recent history of the measured data.

Chart data can be analyzed using the “Graph Pallet”.

To “zoom into” the data displayed, right click in the graph area and de-select “AutoScale X” and/or “AutoScale Y” This will cause the display to stop displaying new data, making it easier to zoom into the data of interest.

Note: Remember to turn AutoScale back on when you are done. No data is lost while AutoScale is off; the screen is just not updated during that time.

By clicking on the magnifier icon you can:

Zoom into a selected area (top left)

Zoom Horizontally (top middle)

Zoom vertically (top right).

Zoom back out to original (bottom left)

Zoom in around the cursor location (bottom middle)

Zoom out around cursor location (bottom right).

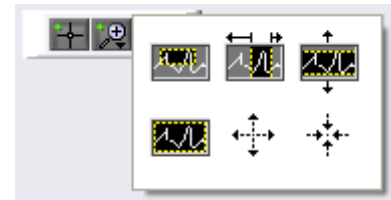
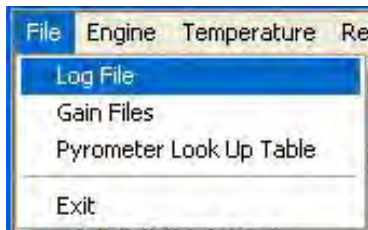


Figure 19 – Zoom Features

## File Menu

### Logging Data to Files

To open the Data Logging window:  
Go to File to Log Files



- The Log File window will appear

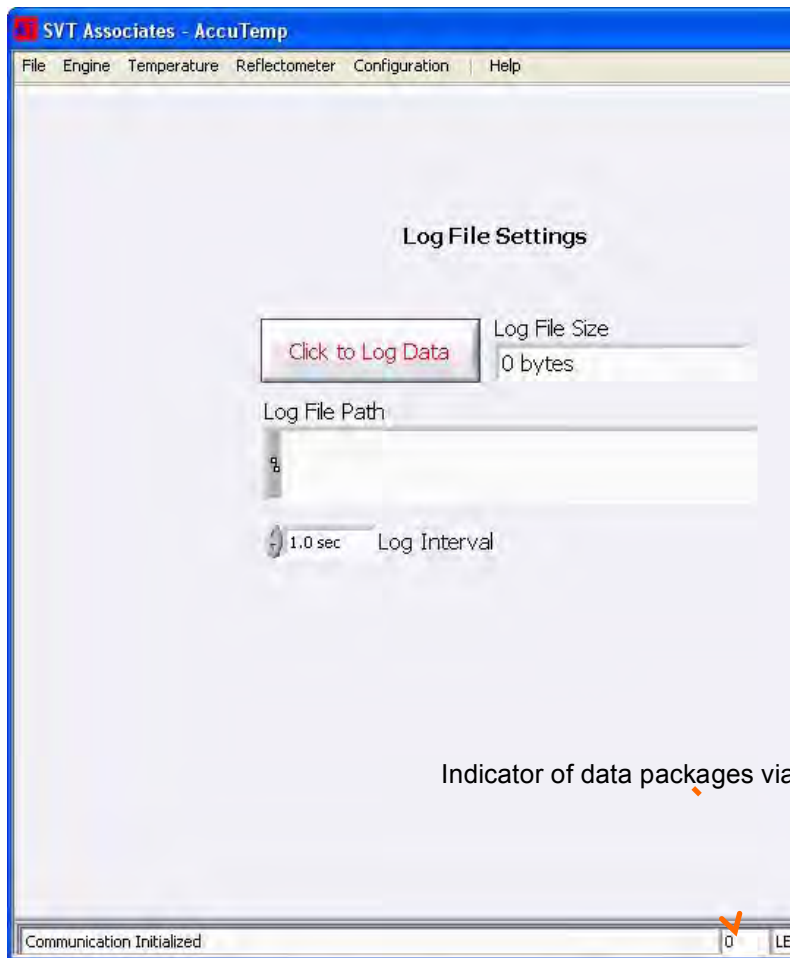


Figure 20 – Log File Window

To activate Data Logging, click the “Click to Log Data” button

- A new window will appear asking you to name and select where to save the log file.



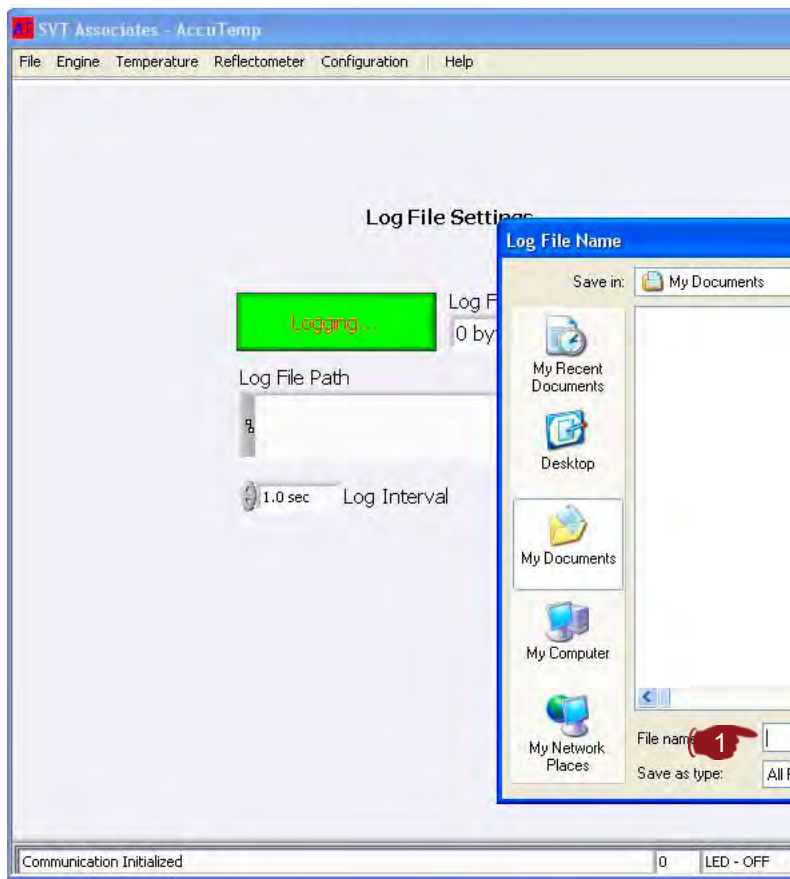


Figure 21 – Log File Window

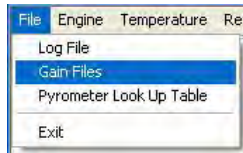
1. Enter a name for the file. The file will be saved as a text compatible file. (\*.txt)
2. Select where you want the file saved
3. Click OK
4. Logging is now active. To turn logging off click the green Logging button. The Status Bar shows if logging is activated or not (ON/OFF).

## Electronics Calibration and Gain Filter

When installing and running the software on the computer for the first time, the factory calibration values for electronic and optical gain will be transferred from the supplied DVD to the computer hard disk but will not be used by the program until instructed to do so by the user. There are 5 files to be loaded by the user, and once they have been loaded, they are automatically saved by the program and need not be reloaded again on that computer.

To reset the hardware amplifier gain and offset values back to factory defaults, follow the instructions below:

To open the gain files control screen  
Go to File to Gain Files



- The Gain Files window will appear

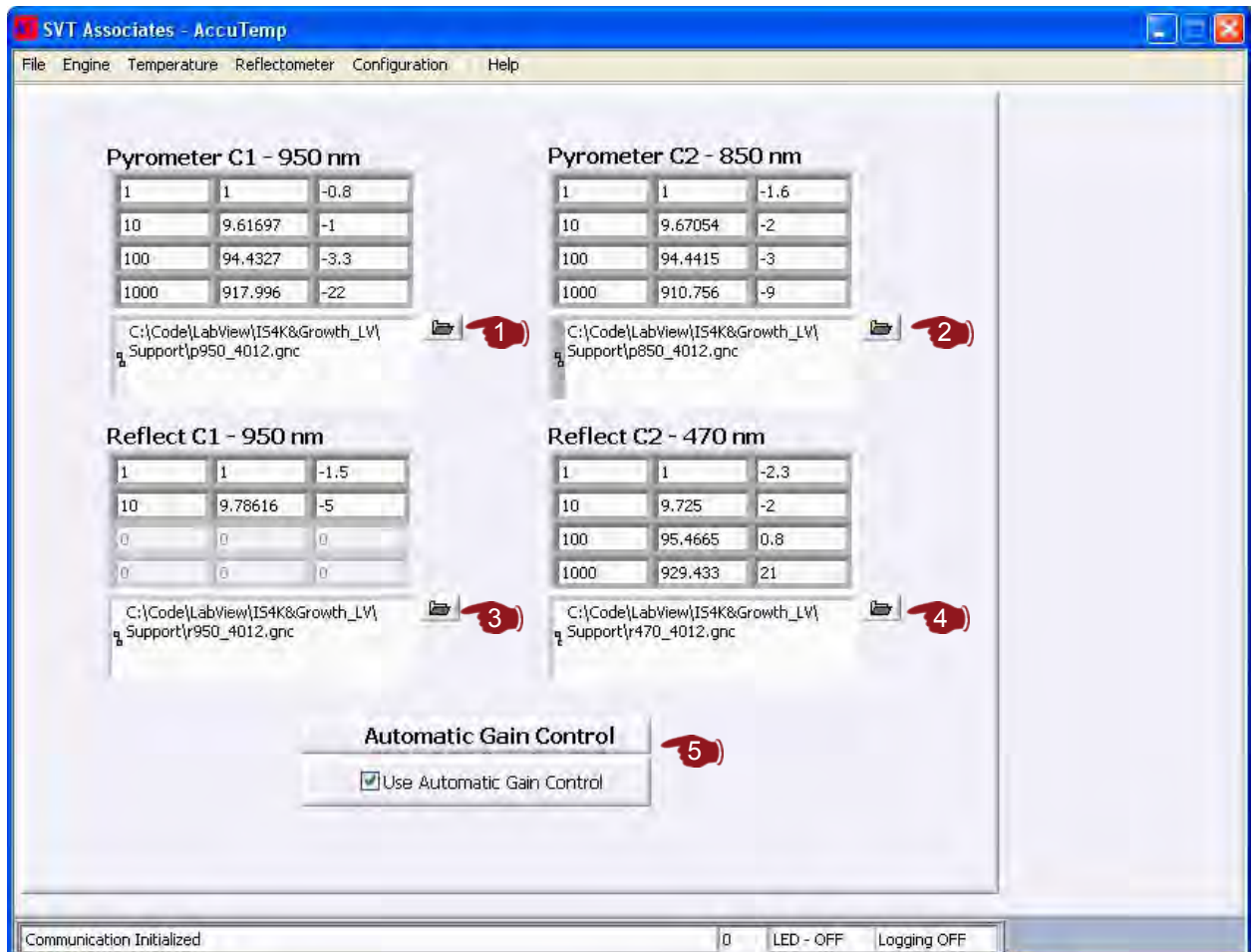


Figure 22 – Gain Files Window



1. Click on the Pyrometer C1 950 nm Gain channel File Browse button and browse to the location containing the gain files and load P950\_4XXX.gnc (where 4XXX is the serial number of your particular optical head)
2. Click on the Pyrometer C2 850 nm Gain channel File Browse button and browse to the location containing the gain files and load P850\_4XXX.gnc (where 4XXX is the serial number of your particular optical head)
3. Click on the Reflect C1 950 nm Gain channel File Browse button and browse to the location containing the gain files and load R950\_4XXX.gnc (where 4XXX is the serial number of your particular optical head)
4. Click on the Reflect C2 470 nm Gain channel File Browse button and browse to the location containing the gain files and load R470\_4XXX.gnc (where 4XXX is the serial number of your particular optical head)
5. The Gain Files Setup window allows you to enable “Automatic Gain Control” where the computer determines the need to switch from one of four hardware gain states depending on the intensity of the signals being received. Check the box next to Use Automatic Gain Control to activate; the system will use the threshold intensity values to cause the software to switch to a higher or lower gain. Changing from one gain state to another takes a few seconds and will prevent the acquisition of data during that time. Automatic gain control is recommended for the Pyrometry channels as the range of detected signal varies by several orders of magnitude as the temperature changes. Manual gain control is often sufficient for the reflectometry channels as the expected changes in reflectance are not as large. Since the signal intensity for the pyrometry channels are always near each other, the gain control for both the 950 nm and 850 nm channels are forced to be the same at all times.

### Manual Gain Control

Each of the four detection channels allows varying ranges of electronic gain depending on the intensity of the signals reaching the instrument. The two pyrometry channels (channels 1 and 2) and channel number 4 each allow four different gain settings labeled 1 to 1000 and channel 3 allows two gain settings labeled 1 and 10. The In-Situ 4000 Engine instrument allows the user to manipulate the gain ranges of each channel by clicking on the handle and selecting the desired gain. See Engine window.

The signal values displayed in the Engine Instrument window are the measured intensities in mV. For optimum signal to noise ratio, the following gain ranges are recommended:

Intensity (mV)	Gain Setting
> 200	1
20 – 500	10
2 – 50	100
< 5	1000

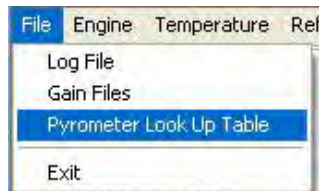
If the gain range is set too high, then the electronic amplifiers may saturate, so one must use manual gain settings with care.

If manual gain control is active, the gain may be conveniently changed on the main Engine window by selecting settings from the pull down menus.

## Temperature LUT Calibration

This procedure loads the proper translation table for generating temperatures from the ratio of the two pyrometry intensities.

Go to File to Pyrometer Look Up Table



- The Pyrometer Look Up Table window will appear

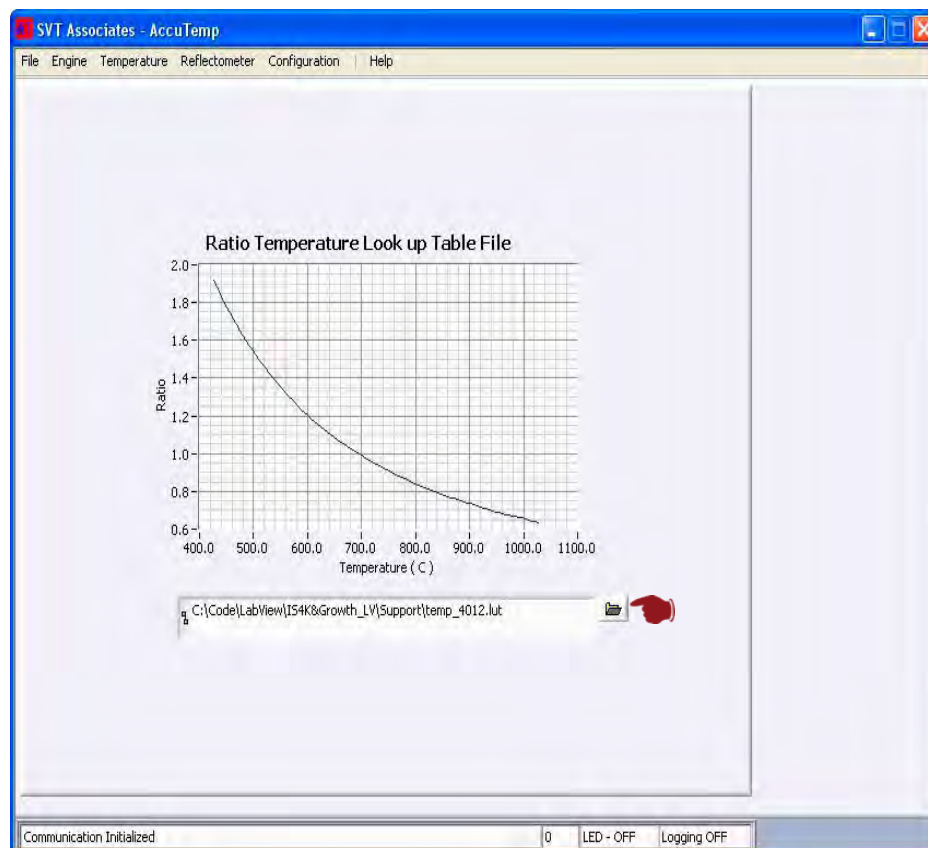


Figure 23 – Pyrometer Look Up Table Window

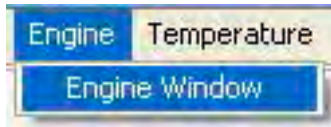
The factory provided LUT file is generated for a “Silicon Substrate” radiator from a calibrated silicon substrate target.

Click Browse and navigate to the temperature LUT calibration file found on the factory calibration DVD. See Appendix LUT for further information (Page 40).

## Engine Menu

### Operation of the Engine Instrument

To open the Engine Window  
Go to Engine to Engine Window



- A separate window will appear
- This window acts as the main interface to collect data and operate the hardware.

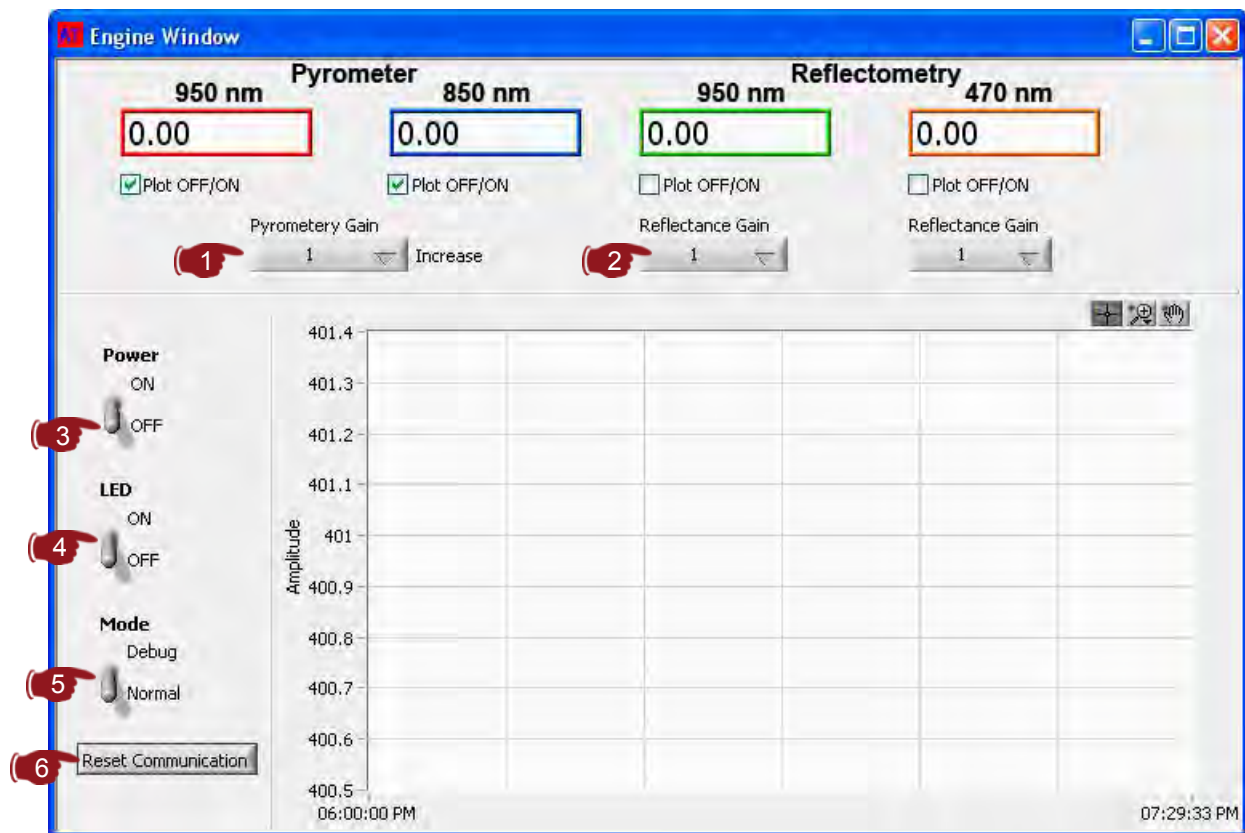


Figure 24 – Engine Window

1. Pyrometry Gain: these fields allow manual gain adjustment of the signal channels. (See Page 20)
2. Reflectance Gain Buttons
3. To start data collection from the optical head, click on the Power toggle switch. Turn it to the "ON" position. The Status Bar shows the status of communication.
4. Turn on the LED illuminators on the optical head by clicking the LED switch. The Status Bar shows the status of the LEDs (ON/OFF).
5. The Debug/Normal switch provides diagnostic information on the internal operation of the optical head. When the debug mode is enabled, the 950 nm pyrometry channel displays the intensity of

the outgoing 950 nm LED, the 850 nm pyrometry channel displays the intensity of the outgoing 470 nm LED, the 950 nm reflectance channel displays the internal temperature of the optical head in °C, and the 470 nm reflectance channel displays the amplitude of the optical chopper. Please consult SVT Associates for diagnostic help if needed.

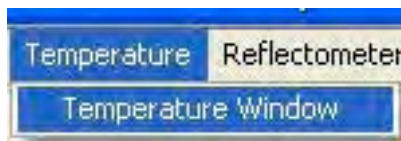
#### 6. Reset Communication button

In case the software lost communication to the optical head click the “Reset Communication” button to reset the COM port. It will flash the COM buffer and restarts communication. You can also toggle the power handle to achieve the same result.

## Temperature Menu

### Temperature Window

Go to Temperature to Temperature Window



- The Temperature Window will appear

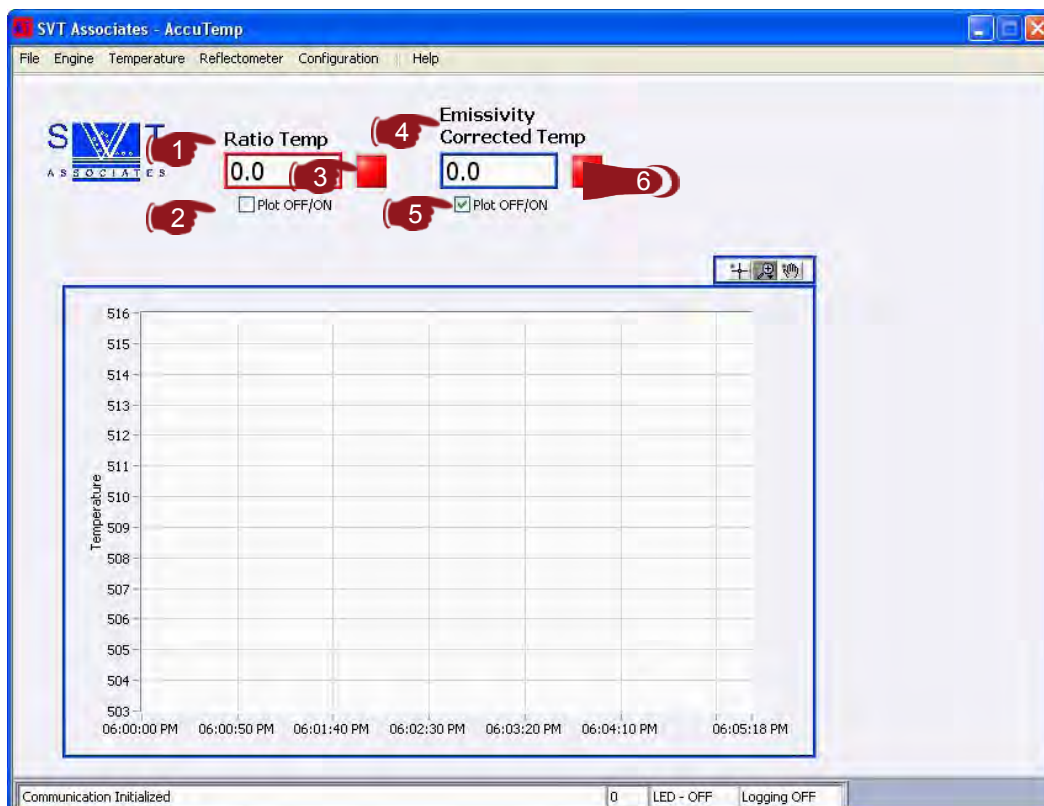


Figure 25 – Temperature Window

1. Ratio Temp
2. Select if you want to plot this temperature



3. If this is red there is a problem and the instrument cannot plot, if it is green the instrument is getting data.
4. Emissivity Corrected Temp
5. Select if you want to plot this temperature
6. If this is red there is a problem and the instrument cannot plot, if it is green the instrument is getting data.

## Reflectometer Menu

### Reflectometer Window

Go to Reflectometer to Reflectometer Window



- The Reflectometer Window will appear

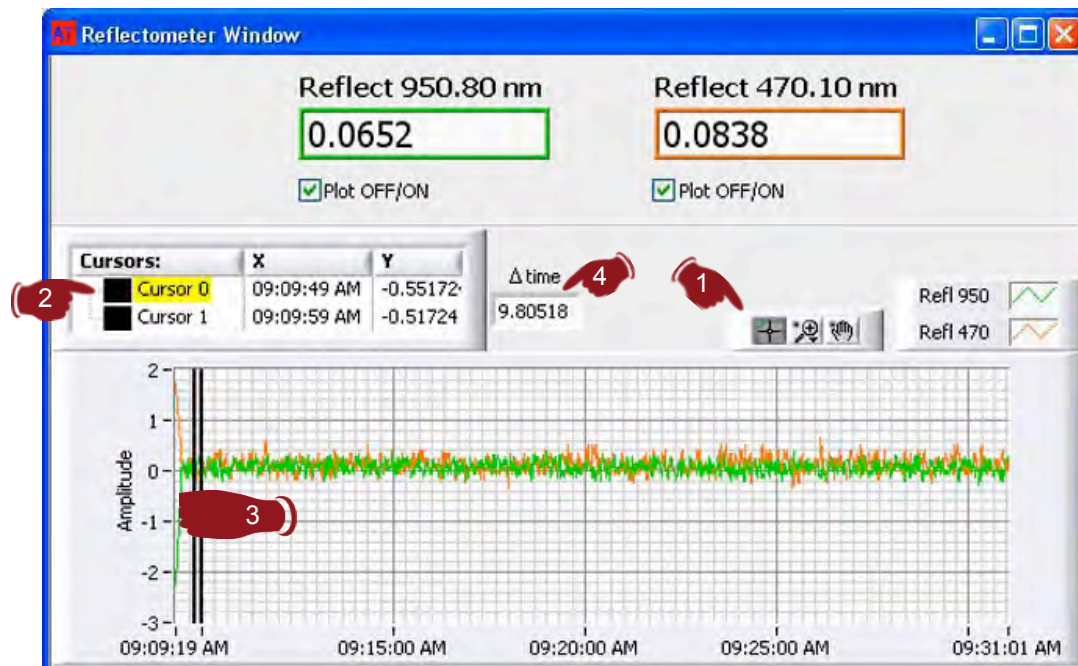


Figure 26 – Reflectometer Window

1. Click on the cursors icon in the graph pallet.
2. Right click on either Cursor 0 or Cursor 1 in the Cursor Legend and select “Bring to center”.
3. Click and drag the cursor to the point of interest.
4. When both cursors are positioned in the window, the “Δ Time” window will display relative time between the cursors.

**Note:** Calibration is required prior to use. See Reflectance Calibration.

## Configuration Menu

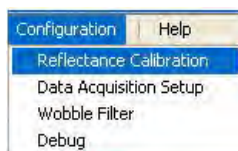
### Calibration of the Reflectometer Instrument

The specular reflectance is computed from the raw reflectometer data and is displayed in the Reflectometer instrument graph. Both the 950 nm and 470 nm channels are displayed simultaneously and the graph axes are manipulated in the same manner as previously discussed. The reflectometer measures reflected light in millivolts and two calibration steps must be performed to allow the translation to specular reflectance.

The instrument must be provided two cases of known reflectance to compute specular reflectance. Typically this is performed with a zero reflectance case and the known reflectance of the substrate under measurement. The zero reflectance case can be performed with the substrate missing (i.e. the reflectometer measuring a diffusing scattering surface) or preferable tilt the substrate slightly so the reflected image of the LED is no longer visible in the video image. Another option is to cover the LED's so they cannot be seen in the video monitor. This case represents a baseline measurement for which stray LED light is accounted in the calibration. The substrate is then restored to its normal tilt position, the LED reflection is visible in the center of the video image or the LED's are uncovered. You can calibrate the reflectance under this condition because the substrate reflectance is assumed to be known such as for a bare semiconductor wafer.

### Reflectance Calibration

Go to Configuration to Reflectance Calibration



- The Reflectance Calibration window will appear.

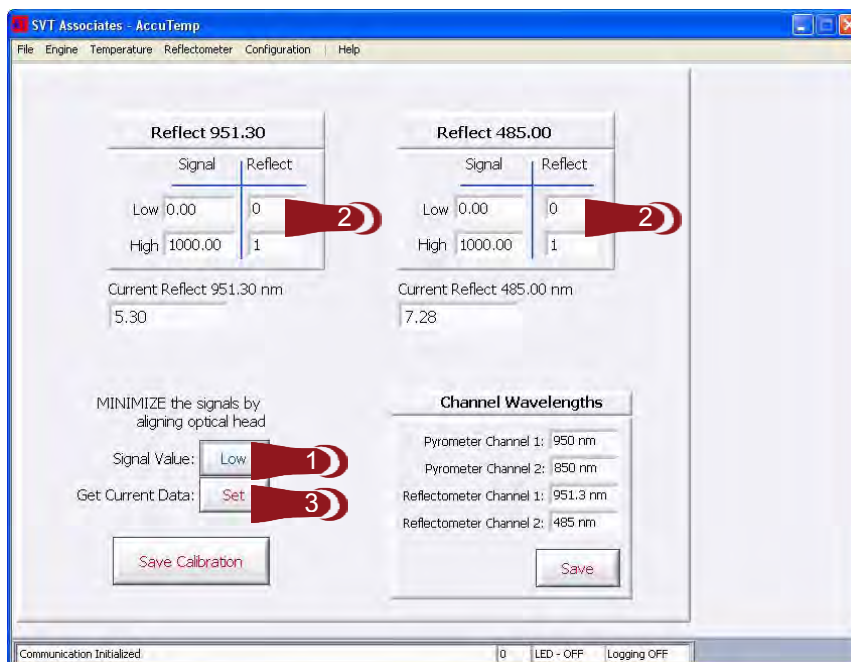


Figure 28 – Reflectance Calibration Window – Low

Cover the LED's so the LED reflection is no longer visible on the video image. Wait at least 3 seconds for the reading to stabilize.

**Note:** Add time of wobble period plus a safety factor if the Wobble Filter is turned on.

Perform the “Calibrate Reflectance → Low Value” option.

1. Click the “Signal Value” button and select Low
2. Enter 0.0 for the reflectance in “Low / Reflect” for both the 950 nm and 470 nm reflectometer as the reflectance is zero with no substrate reflection.
3. Click “Get Current Data” Set button to set the Low Signal reflectance values. This will place the current measured reflectance values into the “Low / Reflect” windows.

Remove the cover from the LED's to show the LED reflection in the video image. Wait at least 3 seconds for the reading to stabilize.

**Note:** Add time of wobble period plus a safety factor if the Wobble Filter is turned on.

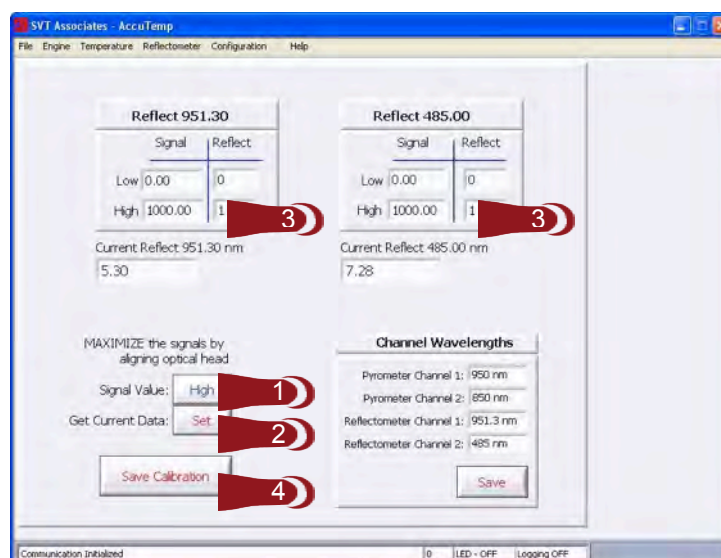


Figure 29 – Reflectance Calibration Window – High

4. Click the Signal Value button and select High
5. Click “Get Current Data” Set button to set the High Signal reflectance values. This will place the current measured reflectance values into the “High / Reflect” windows.
6. Enter the values for reflect 950 nm and 470 nm respectively (See Appendix Page 40). Use known reflectance value or data from literature.
7. Select “Save Calibration” to save these settings.

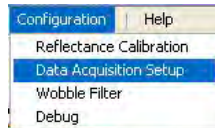
Keep in mind that viewport coating will affect the reflectometer calibration, so routine calibration of the reflectance is advised.

## Channel Wavelengths

The Channel Wavelengths box provides information on your optical head configuration. The actual wavelengths used for computation are: 950 nm, 850 nm, 650 nm, and 470 nm. Refer to your In-Situ 4000 calibration sheet for values specific to your setup. Save the values after entering for future use.

## Data Acquisition Setup

Go to Configuration to Data Acquisition Setup



- The Data Acquisition Setup window will appear

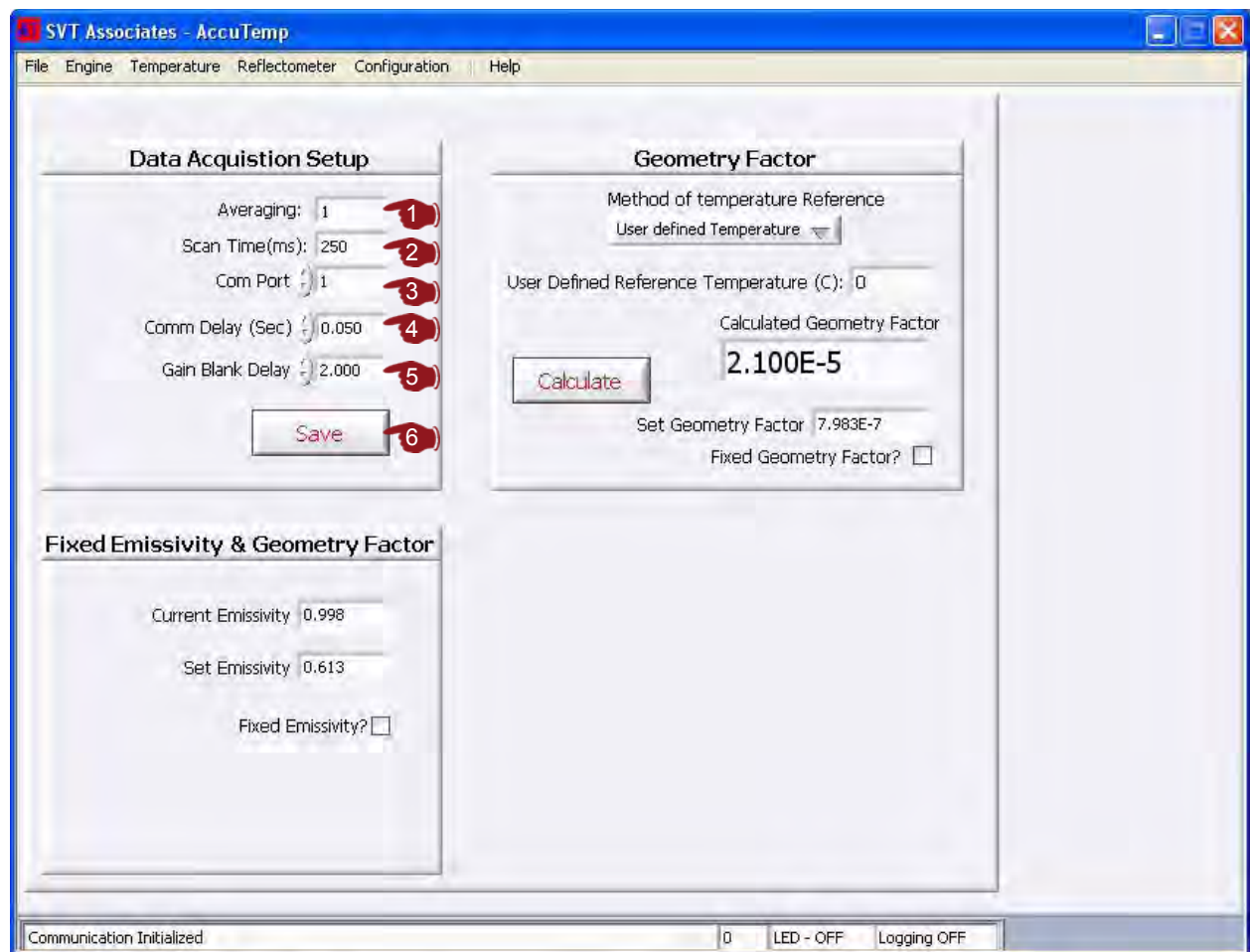


Figure 30 – Data Acquisition Setup Window

1. **Averaging** – Sets the number of data points to be averaged to minimize noise in graphs typically values from 1 – 4 are used.
2. **Scan Time** – Sets the S232 port numbers that will be used to communicate with the In-Situ 4000 Process monitor.



3. **Com Port** – The RS232 port numbers that will be used to communicate with the In-Situ 4000 Process Monitor.
4. **Comm Delay (Sec)** – Sets the polling rate for reading data at the RS232 port.
5. **Gain Blank Delay** – Sets the timeout after a gain change is made (AGC or Manual). This allows the signal to stabilize.
6. **Save** – Saves Data Acquisition values.

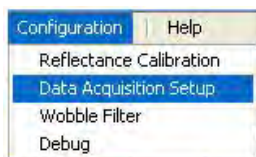
### Calibration of the Temperature Instrument

The temperature instrument can compute temperature in two different ways: by the “two-color” or “ratio” method and single color radiometry. The intended use of the In-Situ 4000 is to use the two-color “ratio” method to provide the reference calibration for the single-color radiometry method. The reason for this is three-fold:

1. There is more noise in the ratio method compared to the radiometric method.
2. The two-color method only applies to “gray body” surfaces and is not correct when multiple-layer dielectrics are deposited on the surface of the substrate. Multiple layer optical interference alters the emissivity at the two different wavelengths and the ratio calculation is then in error. Thus the two-color method is only useful before thin films are deposited.
3. The single-color method may be used even when multiple-layer interference occurs because the In-Situ 4000 has the ability to measure the emissivity at the same wavelength as the single channel pyrometry.

The Temperature instrument has a dialog box that allows you to use the ratio temperature method to calibrate the single channel 950 nm pyrometer when it is valid to do so.

Go to Configuration to Data Acquisition Setup



- The Data Acquisition Setup window will appear

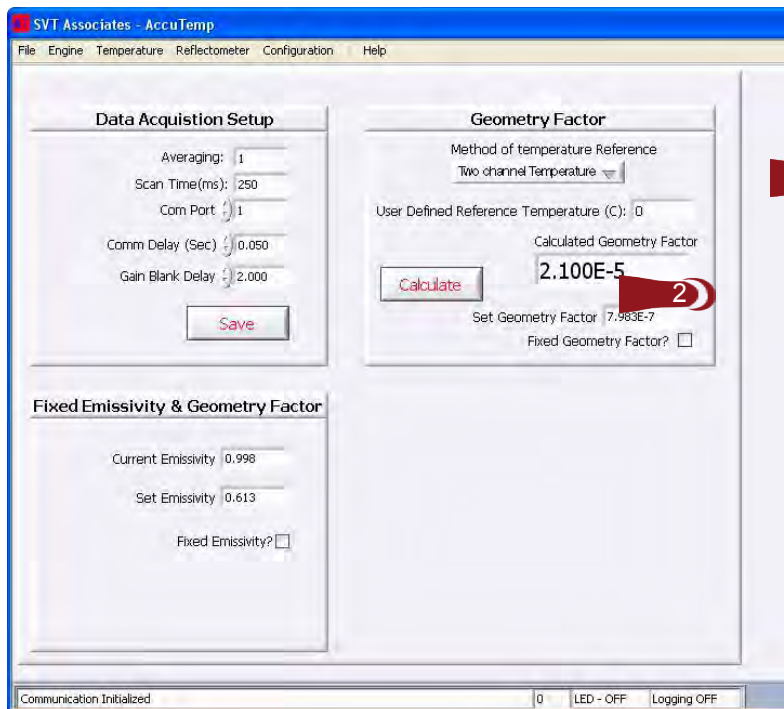


Figure 31 – Data Acquisition Setup Window

In the Geometry Factor box

1. Under Method of temperature Reference select “Two Channel Temperature”
2. Click Calculate

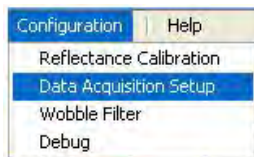
The single channel temperature channel is now calibrated by means of the ratio or two-color channel.

**Note:** Make sure there is sufficient signal strength available to make a reliable ratio calculation (i.e. temperature > 550 °C).

However, there are instances where the ratio method is not applicable. If the heated surface has a significant difference in the emissivity between the two pyrometry wavelengths, then the ratio calculation will be in error. For example, the ratio measurement for a silicon substrate may be different than a GaAs substrate at the same temperature. To properly handle these material differences, the ratio to temperature conversion is performed by a look-up-table (LUT) that can be altered. See Appendix for more information (Page 40).

Alternately, the single channel pyrometry calibration may be performed via other means. For example, the aluminum/silicon eutectic point at 577 °C is often used to sense the substrate temperature. To calibrate the single channel temperature method by other means:

Go to Configuration to Data Acquisition Setup



- The Data Acquisition Setup window will appear

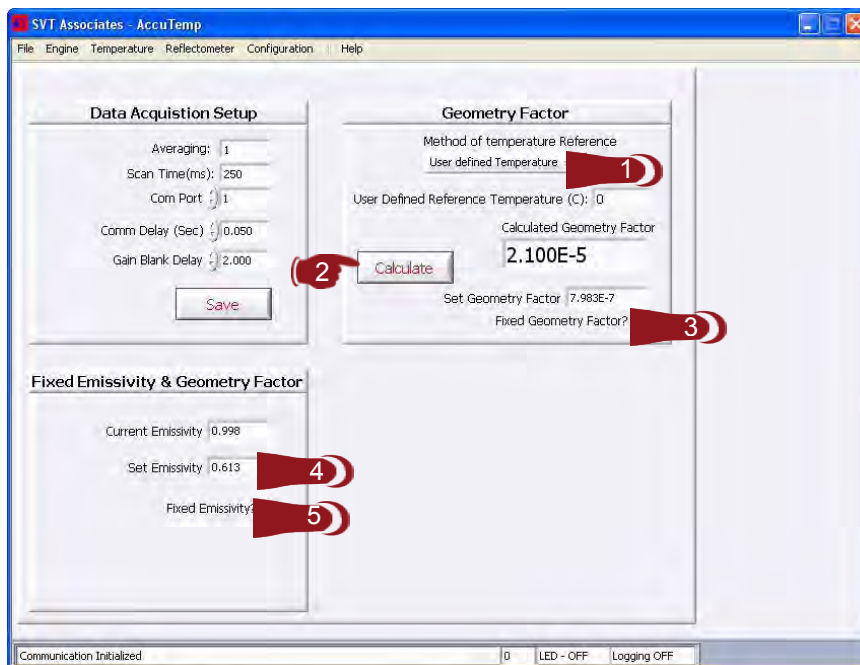


Figure 32 – Data Acquisition Setup Window

In the Geometry Factor box

1. Under Method of temperature Reference select “User defined Temperature”
2. Click Calculate
3. If you know the geometry factor number you want to use, enter it in the box and click “Fixed Geometry Factor?” Box to activate it.

### Fixed Emissivity and Geometry Factor box

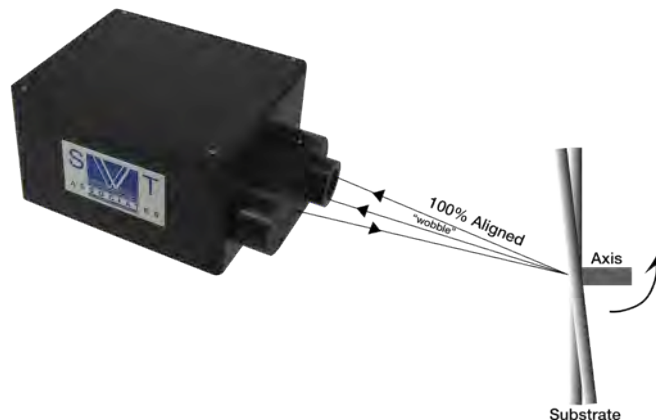
4. The In-Situ 4000 can be operated as pyrometer without emissivity correction. In this case enter a value for set emissivity.
5. Select the "Fixed Emissivity?" check box.

Now the temperature is calculated only by using the 950 nm pyrometer channel. This method is useful for non-specular substrates or when the reflectometer cannot be calibrated.

The single channel temperature channel is now calibrated by means of the "User defined Temperature". Other methods such as Oxide desorption can also be used.

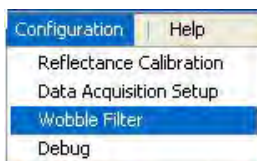
### Wobble Filter

Many thin film processes utilize substrate rotation to help produce more uniform thin films. This mechanical motion can produce strong errors in the reflectance measurement if the surface tilts when rotating. If the substrate is mounted such that the axis of rotation deviates from the surface normal by more than 0.5 degrees, then the reflection of the LED illuminators will appear to "move" around the video image and the measured reflectance will vary. If the tilt is large enough, then the LED reflection will completely leave the field of view and the reflectance measurement will fall to zero.



A special software filter has been implemented to address this problem. It calculates the approximate rotation rate of the substrate and looks back one rotation period in history to find and return the highest reflectance value observed. Thus the reflection can completely leave the field of view for a short time and the reflectance value can be preserved during the interruption.

To activate the Wobble Filter  
Go to Configuration to Wobble Filter



- The Wobble Filter Window will open

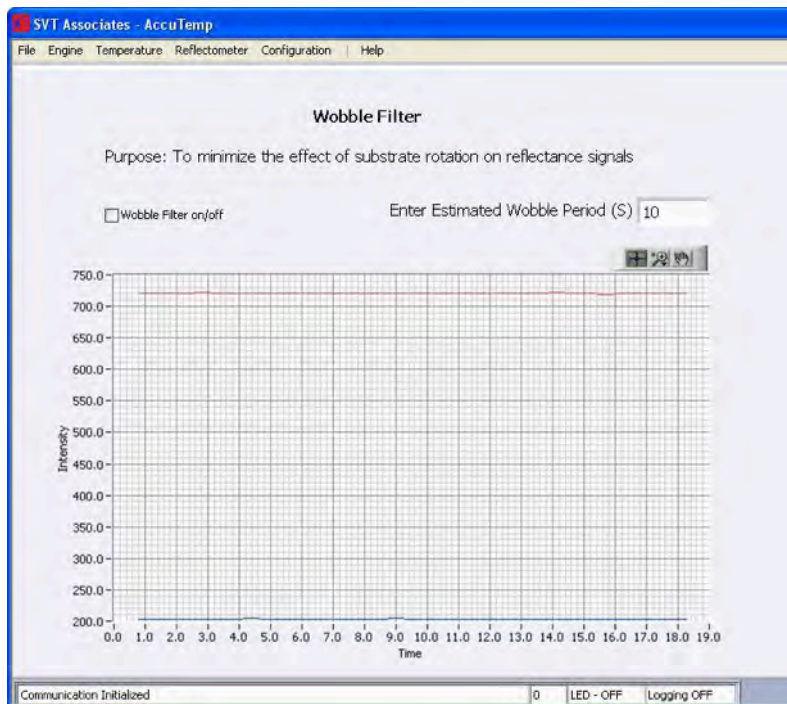


Figure 33 – Wobble Filter Window

Enter an estimated value for the filter keeping in mind that the response time of the reflectometer is slowed down by the time specified in the filter period. The entered value is the period of rotation of the substrate. After several rotations the unit automatically calculates the period.

**Note:** Press enter after entering a value to activate the wobble filter.

## Specifications

Temperature Range .....	450 – 850 °C, or 500 – 1200 °C (others on request)
Compatible Substrates .....	Silicon, GaAs, GaSb, InP, Sapphire (backside coated)
Radiometer Wavelengths .....	950 nm, 850 nm
Temperature Equivalent Noise .....	< 0.5 °C RMS at 450 °C, 0.05 °C RMS at 600 °C
Target Distance Range .....	400 mm to infinity
Pyrometry measurement Spot on Target .....	20 mm diameter at 500 mm target distance
Reflectometer Field of View .....	3.6 degrees
Auxiliary Output .....	TTL signal of internal chopper waveform to allow synchronization to external reflectance illuminators or laser scattering illuminators
Viewport Requirements .....	Minimum vacuum viewport size is 2.75 inch Conflat flange, at normal incidence to wafer. Minimum clear aperture is 33 mm diameter. Transmission range 470-950 nm
Focus Adjustment .....	Manual
Operating Ambient Temperature .....	18 °C to 25 °C, <2 °C thermal drift during use
Storage Ambient Temperature .....	-40 °C to 50 °C
Relative Humidity .....	Non-condensing
Power Requirements .....	120 V/220 V 50/60 Hz wide input
Power Cable Length .....	2 m
Weight .....	3.2 kg (not including external power supply)
Housing .....	Black anodized aluminum
Dimensions .....	100 x 140 x 90 mm (optical head)

### COMPUTER REQUIREMENTS

Operating System .....	Windows XP or later
Computer Interface .....	RS232, 9 pin D male connector (AT standard)

### OPTICAL ALIGNMENT VIDEO SYSTEM

Video Camera Output .....	B/W RS170 signal at 60 Hz, 75 Ω BNC connector. CCIR at 50 Hz is also available.
Video Cable .....	75 Ω BNC coaxial cable, 2 m length
Video Monitor .....	8.4" Color, RS170, Input, 24 V DC

### OPTIONAL ACCESSORIES

220 V power supply  
Alternate reflectometer wavelengths available  
Remote/External illuminator reflectometer available for non-normal illumination  
Analog output for feedback control



## Appendix

### Index of Refraction Values

Below is a list of useful index of refraction values for common substrate material. These may be used for reflectometer calibration. See Reflectance Calibration on page 29.

Material	950 nm Index	470 nm Index
Silicon	3.67 + i0.005	4.32 + i0.07
GaAs	3.54 + 0.08	4.33 + i0.44
Ge	4.65 + i0.3	4.3 + i2.4
AlAs	2.974 + i0.00	3.51 + i0.00
GaSb	4.3 + i0.34	4.3 + i2.3
InAs	3.7 + i0.43	4.3 + i1.8
InP	3.37 + i0.2	3.818 + i0.5
InSb	4.42 + i0.64	3.57 + i2.2
GaP	3.17 + i0.00	3.6 + i0.01
GaN	2.37 + i0.00	2.47 + i0.00

These values are obtained from the Palik database (Handbook of Optical Constants of Solids, Edward D. Palik, Academic Press, First edition 1985, 2nd Edition 1991) and the Landolt-Bornstein tables (Semiconductors: Group IV Elements and III-V compounds, O. Madelung ed., Springer-Verlag, 1991). The data for GaAs is based on ellipsometry measurements by Aspnes et. al. (Phys. Rev. B 27, p. 985 (1983)).

### Reflectance of an assortment of substrate materials (at normal incidence and at room temperature)

Substrate	950 nm Reflectance	470 nm Reflectance
Silicon	0.326	0.419
Ge	0.419	0.492
GaAs	0.313	0.438
GaSb	0.39	0.48
InAs	0.33	0.454
InP	0.305	0.349
InSb	0.41	0.45
Sapphire	0.075	0.078

These values are obtained from the Palik database (Handbook of Optical Constants of Solids, Edward D. Palik, Academic Press, First edition 1985, 2nd Edition 1991) and the Landolt-Bornstein tables (Semiconductors: Group IV Elements and III-V compounds, O. Madelung ed., Springer-Verlag, 1991). The data for GaAs is based on ellipsometry measurements by Aspnes et. al. (Phys. Rev. B 27, p. 985 (1983)).

## Editing the Ratio LUT

The translation from pyrometry intensity ratio to temperature is performed using a look up table (LUT). A LUT was chosen because many semiconductor substrates are not ideal grey body emitters and the emissivity is different between the 950 nm and 850 nm wavelengths. In fact, not only is the emissivity different, but the emissivity ratio for those channels will be different for different substrate materials and will even change with temperature. Rather than trying to compute the emissivity ratio to temperature response from first principles, a more practical method is to empirically measure the ratio for each substrate of interest. The resulting measurement is captured in a LUT.

The ratio LUT is a series of discrete ratio - temperature data points from which the Temperature instrument linearly interprets temperature. A factory calibrated ratio LUT for a silicon substrate is provided with the instrument. Alternate substrate materials will require the user to generate a LUT specific for that material. Making a new LUT requires that the user perform a pyrometry ratio measurement simultaneous with an independent temperature measurement such as the aluminum melting point measurement. (See page 33 – Calibration of the Temperature Instrument) Other temperatures can then be used with the pyrometry 950 nm single channel temperature.

## Mapping a new LUT

You may generate a new LUT by recording the ratio measured by the Temperature instrument and measuring the substrate temperature through some independent means such as a thermocouple. The log file of the Temperature instrument provides the ratio measurement to the user and a convenient method for recording the measured temperature is by inserting the temperature value as a comment in the log file. After many different temperatures have been mapped out, the log file is then easily analyzed to extract a table of ratio and temperature values. The new LUT file may then be generated according to the following file format.

The first line in the LUT file must be  
{B74B9D7A-30B7-11D2-AEE0-244611C10000},LUT,1  
This signifies to the program that the file is a LUT file.

Comment lines are inserted with the // notation. The next non-comment line in the file must be the material label line:

Material: Silicon

where the two fields are separated by a tab character. Next, the pyrometer gain range for which this LUT is valid is specified by a line

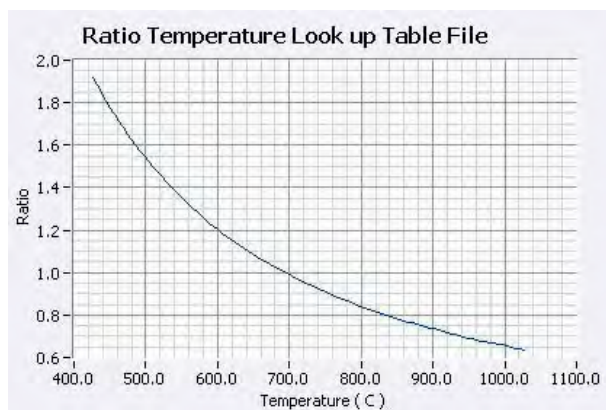
Gain Range: 1

where the gain range may be 1 through 4 and the two fields are again separated by a tab. You must be aware of the gain range when you perform the temperature mapping measurement.

The rest of the LUT is a sorted table of ratio values and temperatures values in degrees C separated by tab characters. There is no explicit limit to the number of entries in the table.

Load in the new LUT text file from the "Load" button in the ratio LUT property page of the Temperature instrument. The new LUT will be saved to the default configuration file on the hard disk so it will automatically be loaded each time the program is run.





```
//Header for file of type LUT
//GUID,Nice Name,Version Number
{B74B9D7A-30B7-11D2-AEE0-244611C10000},LUT,2
//tab delimited lookup table file. First data lines must be:
//Material:<tab>material name
//Gain Range:<tab>valid range #
//The column headings are:
// PI950/PI850 Temp Deg C
Material:      Silicon
Gain Range:    10
0.29214 696.4
0.29216 674.1
0.29215 674.2
0.29210 674.3
0.29213 674.4
0.29207 674.4
0.29208 674.5
0.29522 669.8
0.31779 629.8
0.33363 604.8
0.34578 586.8
0.36415 575.7
0.36905 568.5
0.37272 563.5
0.37537 559.8
0.37726 557.2
0.37888 555.1
0.38003 553.5
0.38089 552.2
0.38164 551.2
0.38410 549.6
0.41289 522.9
0.44201 494.7
0.47364 472.8
0.48899 458.0
0.50190 447.2
0.50930 438.6
0.51122 431.8
0.51642 426.3
0.52255 422.1
0.52605 418.6
0.52232 415.3
0.52443 413.2
0.51766 410.7
0.52750 408.4
```

Figure 35 – Example LUT File

## Bandgap Based Temperature Measurements

### Introduction

Emissivity corrected pyrometry relies upon measurement of surface black body radiation as long as temperature is high enough and the substrate is opaque. To overcome this limitation the In-Situ 4000 Process Monitor provides bandgap based thermometry as add-on. Band-edge based thermometry utilizes the temperature dependence of a semiconductor bandgap to determine substrate temperature. A typical setup is shown in figure XX.

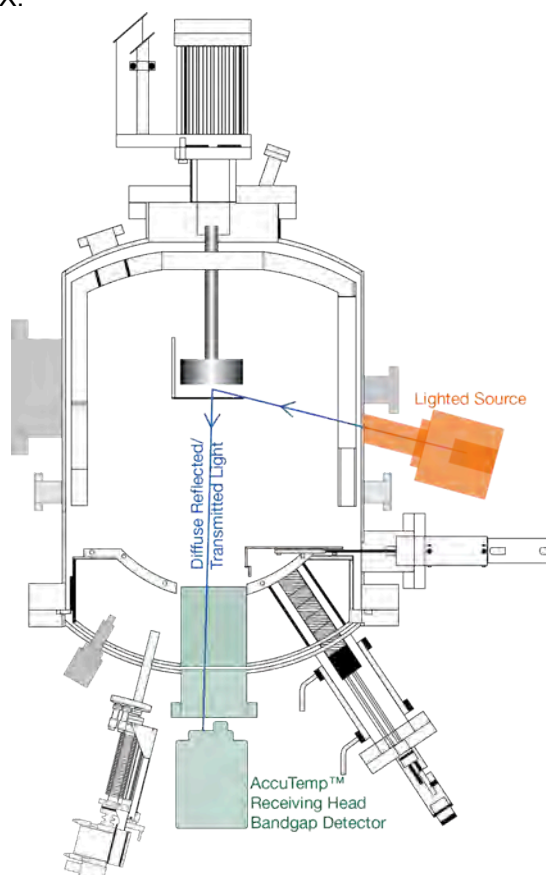


Figure 36

For higher temperatures substrate heater radiation can be used to determine bandgap, for low temperatures an auxiliary light source needs to be used. In the first case scattered transmitted light and the latter case diffuse reflected light is analyzed in the Receiving Head.

Both emissivity corrected pyrometry and band-gap thermometry work well for GaAs, InP, and Si substrates, however, the general usable temperature range is limited with each. Pyrometry can measure temperatures from 400 °C and higher, band-gap thermometry is limited to temperatures typically below 650 °C due to free carrier absorption and black body radiation. Since pyrometry relies on absolute intensity measurement it is affected by viewport coating and stray light from hot sources. Using ratio or 2-wavelength pyrometry can eliminate some of the interference problems but during growth is of limited use since emissivity changes are not properly accounted for. Transparent substrates such as SiC, ZnO and others cannot be measured by pyrometry unless a backside opaque coating is applied to the substrate. Bandgap based monitoring relies on the spectral change in intensity as a relative characteristic to determine bandgap. As such it is not limited and can be used in these cases. However,

different substrates may require different spectral ranges and detector configurations. Double side polished substrates also cannot be measured well with the bandgap based technique in reflection mode due to low light scattering efficiency.

Pyrometry is not affected by material properties of the grown layer. However, the signal for band-gap thermometry is attenuated by materials having smaller bandgap energy. This degradation depends on layer thickness (<1 micron) but deteriorates measurement performance over time. Once an opaque layer has been deposited (<100 nm) pyrometry can in such case take over for uninterrupted temperature monitoring and calibration of the pyrometer. This technique is superior to eutectic melting point calibration. For materials with higher band gap both techniques can be used.

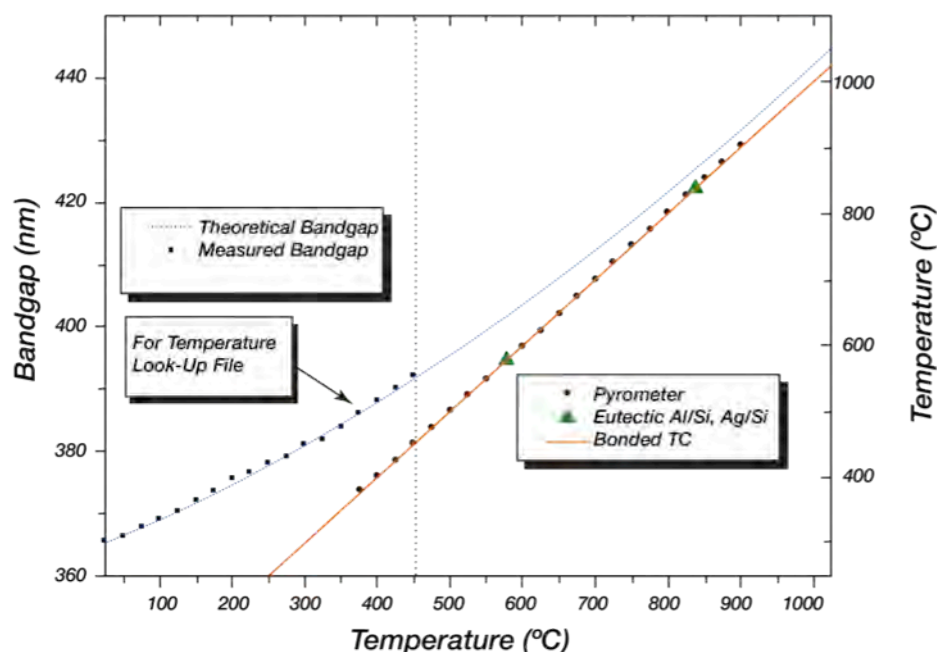


Figure 38 – Combination of pyrometry and band-gap thermometry for GaN temperature monitoring over extended temperature range and for optimum accuracy

During heterostructure growth interference oscillations due to multi-layers occur (see Application note 1401). Emissivity corrected pyrometry accounts for these changes and automatically corrects the temperature readings. However, bandgap thermometry is affected by these oscillations and accurate determination of the bandgap is affected. By using sophisticated derivative analysis this effect can be at least reduced.

## Theory of Operation

Bandedge or bandgap temperature calculation is based on the principle of a semiconductor material's energy gap,  $E_g$ , dependence on temperature. The energy gap (bandgap) is calculated by the following empirical equation:

$$E_g(T, \text{doping}) = E_g(0) - \frac{\alpha T^2}{\beta + T} + E_g(\text{doping})$$

Where,

$E_g(0)$  = Energy Gap at 0K

$\alpha$  = Absorption Coefficient

$\beta$  = Fitting parameter for Phonons

$E_g(\text{doping})$  = Fitting parameter for doping

$E_g(\text{doping})$  is different for different type of materials and must be known in order to correctly find the Energy gap. This is done empirically using a LUT similar to the ratio temperature method. This look up table tabulates the relationship between bandgap and temperature for determination of temperature. The software fits the materials using above equation over the temperature range of interest.

An example of temperature dependence of the Energy gap of GaAs is shown in Figure 37.

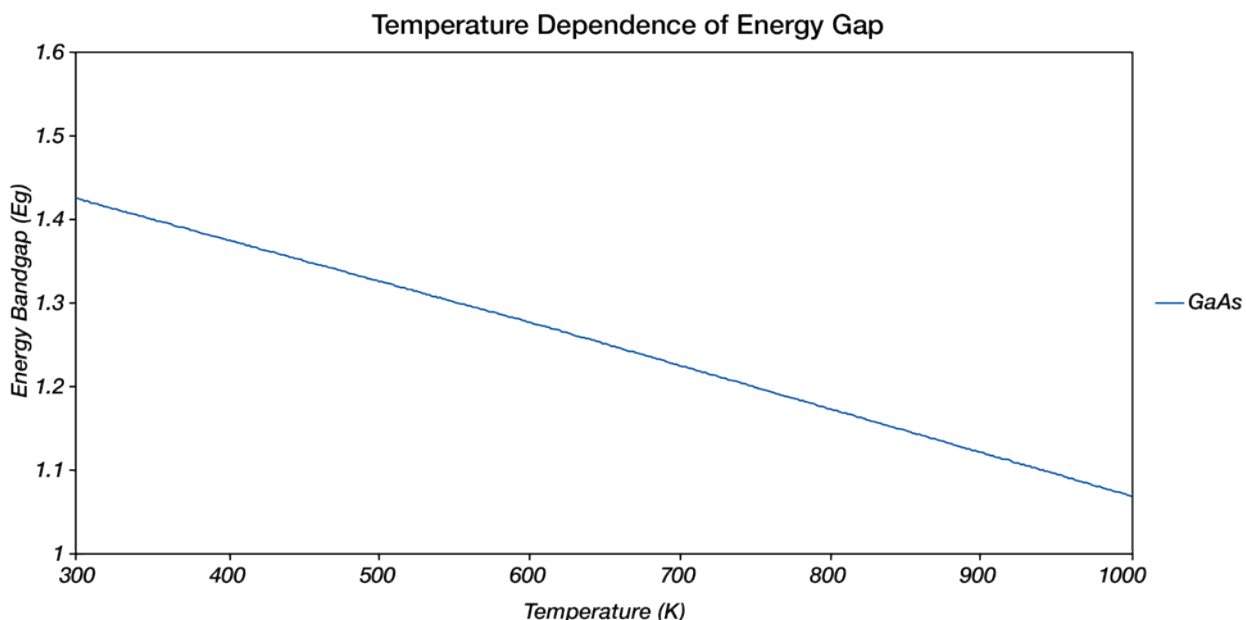


Figure 37 – Temperature Dependence of the Energy gap for GaAs



Some typical values for well-known semiconductors are listed in the table below.

Material	$E_g(0)/\text{eV}$	$\alpha \cdot 10^{-4}$	$\beta$
Silicon	1.1557	7.021	1108
SiC 6H	3.024	-0.3055	-311
GaAs	1.5216	8.871	572
InAs	0.426	3.158	93
InP	1.4206	4.906	327

### Accurate Temperature Measurement

As consequence of above mentioned facts and phenomena a more versatile instrument that combines both measurement methods is desirable. The Accutemp Process Monitor provides high end performance over the entire temperature range.

Below 400 °C emissivity corrected pyrometry cannot be used due to lack of black body radiation. Bandgap based temperature monitoring is the method of choice. At high temperatures bandgap based measurements are impossible due to carrier concentration and radiation intensities. Pyrometry is the method of choice. In the intermediate temperature regime emissivity corrected pyrometry is used for best results on opaque substrates. Precise calibration and repeatability can be achieved with band-gap based calibration. For transparent substrates bandgap based monitoring can provide a good alternative. Once layers become opaque pyrometry can take over for best performance.

The Accutemp Process Monitor combines both techniques in a single instrument. In addition it allows accurate growth rate monitoring using its multi-wavelength reflectometer. This enables precise thickness monitoring, rate monitoring and surface roughness analysis.

Combining emissivity corrected pyrometry and band-gap thermometry in a single instrument provides optimum performance for temperature monitoring during heterostructure growth. The AccuTemp process monitor provides dedicated hardware, an easy to use software interface and ready to use growth recipes. Addition of its spectral reflectometer enables superior process monitoring and control.



## Growth Rate Fitter

The Growth Rate Fitter instrument utilizes data from the reflectometer instrument. When a film is deposited on a substrate of differing index of refraction, the optical reflectance generally oscillates in time due to optical interference effects (see page 7 – Reflectance). The period of the oscillation is directly dependent on the growth rate of the film and the film refractive index. The amplitude, phase and damping characteristics of the reflectance are dependent on the film's complex index of refraction.

The Growth Rate Fitter instrument fits a model<sup>1</sup> of the oscillations to the data in real time to determine the film's optical parameters and growth rate. The fitter can analyze the reflectance data from both reflectometer channels. The acquired data, the model data and the parameter values are all displayed in the instrument's window.

1 See for example, W.G. Breiland and K.P. Killeen, J. Appl. Phys. V 78, p. 6726 (1995).

## Setup

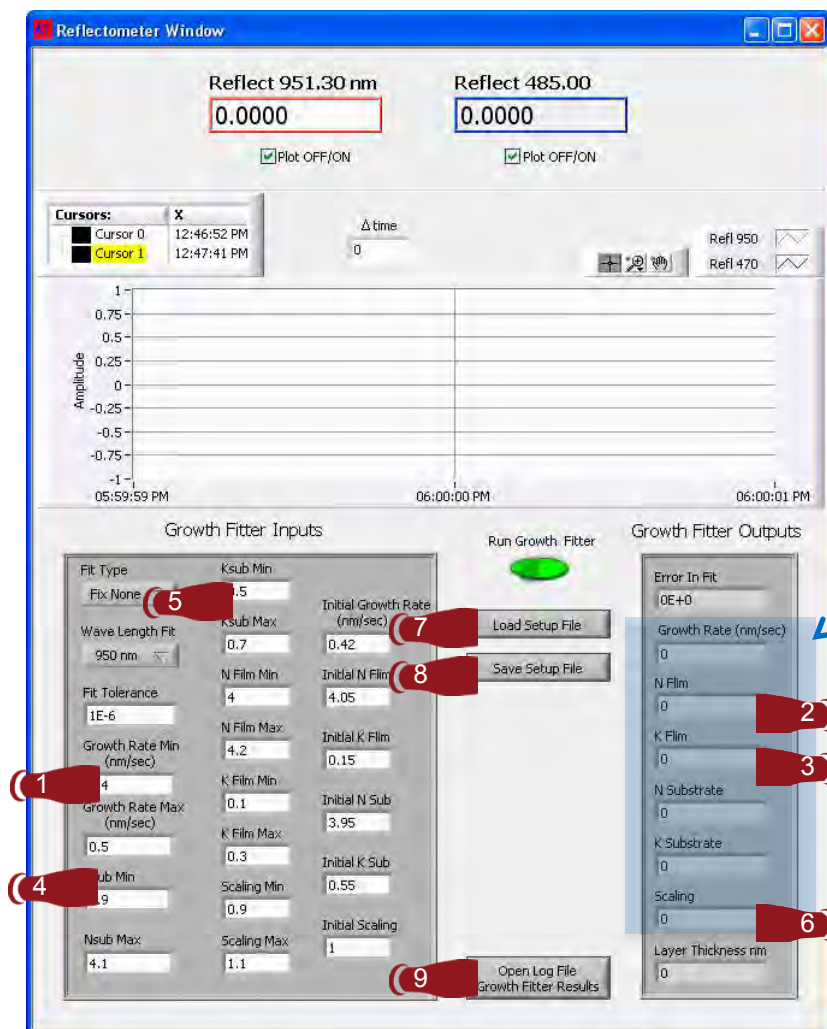


Figure 39 – Growth Fitter Window

The Growth Rate Fitter instrument is installed on the computer during the In-Situ 4000 installation procedure. It will appear in the lower window of the Reflectometer Window. In order to make use of the Fitter several input parameters are required to control the fitting algorithm. These parameters are located on the left side of the screen (see Figure 39).

The fitter uses a Simplex algorithm to minimize the error function of the model. The analytical model used treats any material underneath the currently growing film as a “virtual substrate” described only by a single complex index of refraction. The virtual substrate can be a simple material like the physical substrate itself, or it can be a complex combination of thin film layers on a physical substrate. In any case, the virtual substrate is modeled with a real substrate index of refraction,  $n_{\text{sub}}$ , and imaginary substrate index of refraction,  $k_{\text{sub}}$ .

The model contains the following fit parameters:

1. **G** Growth rate in nm/s.
2. **N** Real part of the film's index of refraction.
3. **k** Imaginary part of the film's index of refraction.
4.  **$n_{\text{sub}}$**  Real part of the effective substrate's index of refraction.
5.  **$k_{\text{sub}}$**  Imaginary part of the effective substrate's index of refraction.
6. **s** A scaling factor used to compensate for reflectance attenuation by unintended coatings deposited on the vacuum viewport window.
7. [Load Setup File button](#) – Load any setup files that have been saved.
8. [Save Setup File button](#) – Saves current settings to a setup file to be available for loading at a later date.
9. [Open Log File Growth Fitter Results](#) – Opens the log file for the Growth Rate Fitter.

The fit algorithm always adjusts the **G**,  **$n_{\text{sub}}$**  and  **$k_{\text{sub}}$**  parameters. The user can specify whether or not to fit the other three parameters. The pull down menu Fit Type selects the scope of fit: Fix None, Fix S, Fix N, Fix K, Fix N,S Fix K,S, Fix N, K and Fix N,K,S. Section of the type of fit impacts its results and convergence and is describes later in this chapter (Controlling the Fit). Another factor influencing the fitter instrument is the Fit Tolerance which acts as a stop measure once the error in fit is below this threshold value.

In addition, the user must provide initial guesses to give the fit algorithm a satisfactory starting place to search for a best fit and a minimum and maximum value. The initial values used in the fit can be the values determined from the last fit or any other guess by the user.

One limitation of interpreting reflectance oscillations is that the fit parameters are not independent from each other for very thin films. For example if a film is being deposited with a current thickness corresponding to less than  $\frac{1}{4}$  optical wave, the fit algorithm can find a satisfactory fit for many different combinations of the six possible parameters which leaves little useful information for the user. As the film becomes thicker, there is more information available to the fit algorithm and the fit parameters “decorrelate” and allow meaningful interpretation of the results. The Growth Fitter algorithm has an adaptive fitting feature, which allows the user to still gain meaningful results in the early stages of growth. The Growth Fitter holds the film **n** and **k** parameters constant at the user supplied “guesses” until it determines that there is enough data to allow them to vary. If the user has specified that the film **n** and **k** be allowed to be fit, then once the film has reached sufficient thickness the fitter frees them and allows the algorithm to modify the values. If the user has specified either of the parameters as fixed, then

they will remain fixed throughout the current film deposition. The fit status of the scaling factor,  $s$ , is not changed by the adaptive fitting.

### Controlling the Fit

The fit algorithm is fairly sensitive to the initial guess provided by the user. The reason for this sensitivity is that the fit error “surface” used to fit the model to the data may contain several local minima. Some of these local minima are almost as “deep” as the true global minimum.

The In-situ 4000 Growth Rate Fitter solves this problem by limiting the parameter space in which the fit algorithm searches. The user specifies how far the fit algorithm may deviate from the initial guess in its search for the true minimum. All parameters except the two virtual substrate indices may be limited in this fashion. Therefore, if the user must has some *a priori* knowledge of the film parameters fitting results will benefit significantly.

**Minimum Rate Allowed:** It is possible for the fitting algorithm to “flat-line” or settle on a seemingly satisfactory fit with a very small (<0.001 nm/sec) growth rate. The solution is to “kick” the growth rate to a more reasonable value if it falls below a certain threshold. However, if the actual growth rate is lower than the threshold, the fit becomes ineffective.

**Maximum Parameter Variation:** These values set boundaries in parameter space beyond which the fitter is not allowed to search. This region is defined as absolute values on either side of user’s initial guess.

### Performing a Stand-alone Fit

Standalone fits are useful for performing deposition rate calibrations or monitoring a very thick film growth. Prior to start the fit the user needs to select the wave length in the pull down menu Wave Length Fit. After that reasonable guesses for the optical parameters of the substrate, the film and the expected growth rate are required. It is possible to open a previously created setup file to reuse parameters for convenience. The fitter uses all data selected between the two cursors Cursor 0 and Cursor 1 in the reflectance chart for its calculations. A click on the Run Growth Fitter button starts the instrument and outputs are generated within less than a second duration. In addition to the growth rate is calculated using the time between cursors and growth rate from the fit. The results of the fitter are stored in a dedicated results file.

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