# Advances in Microelectronics Allowing for Increased Capability in Optical Temperature Measurement

***James W. Knope***
*BASF Catalysts LLC, Portland, Oregon, USA*

*Presented at the 2005 ASM Heat Treating Conference, Pittsburgh, PA*

## Abstract

Advances in microelectronics are allowing for increased capability in optical temperature measurement instruments. New circuit designs allow for significant increases in temperature range, resolution and measurement speed. These improvements open the door for techniques such as background radiation subtraction in plasma processes, measurement of high speed induction heating processes, and digital interface between instrument and control hardware. This paper will focus on using these attributes to measure temperature in:

1. Induction heating processes with short heating times and large changes in temperature: Instrument response times, particularly at lower temperatures, are not typically fast enough to measure high speed processes. Broader range optical instruments with digital outputs can capture these processes, passing on measurements to control hardware.
2. Plasma processing environments where radiation from the plasma is significantly greater than radiation from the target: Plasmas radiate energy at the same infrared wavelengths used to measure temperature. This radiation can easily overwhelm the infrared radiation used to determine temperature. Techniques have been developed which measure and subtract the background plasma radiation from the target measurement leading to a correct measurement of target temperature.

## Introduction

Optical thermometers (or optical pyrometers) have many advantages over thermocouples for measurements where the ability to contact the work piece is limited [1]. Optical thermometers measure radiation emitted from a target at specific wavelengths of light and correlate the emission to the temperature of the target. Figures 1 and 2 show the blackbody radiation curves for two different temperature regions. From these curves, it can be seen why long wavelengths have been used for measuring low temperatures and short wavelengths have been used to measure higher temperatures.

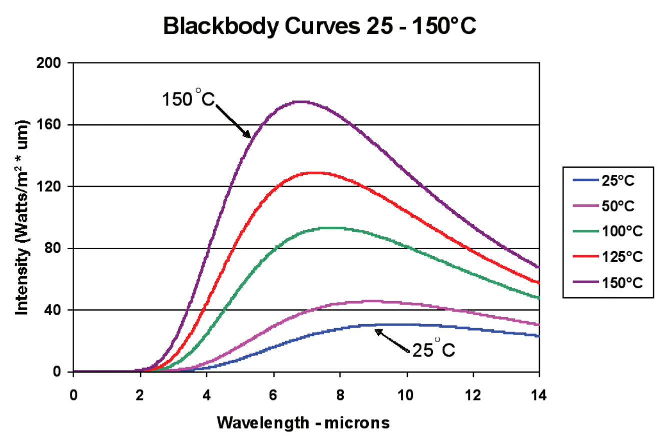



*Figure 1: Blackbody curves for 25 – 150°C. Instruments measuring these temperatures have traditionally used wavelengths in the 8 – 14 micron range.*

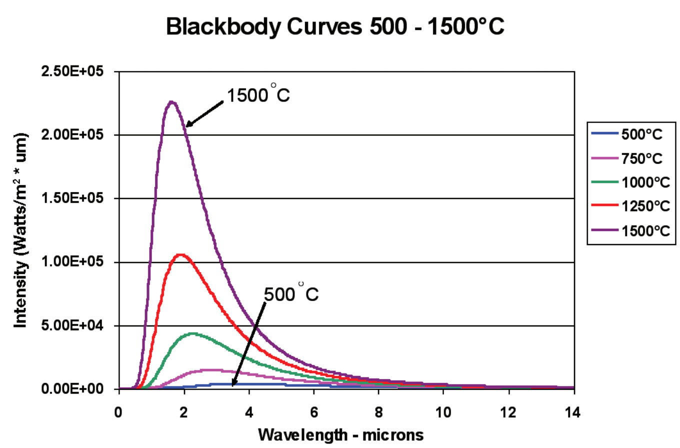



*Figure 2: Blackbody curves for 500 – 1500°C. The higher energies at these temperatures allow short wavelengths to be used for optical temperature measurements. Short wavelength instruments have significantly smaller emissivity errors than long wavelength instruments.*

While long wavelengths can be used for measuring high temperatures, short wavelengths offer many significant advantages and have been the preferred technique for most high temperature applications. Short wavelength measurements are much less sensitive to emissivity and other errors than long wavelength measurements. Figure 3 shows the measurement error caused by a 10% error in emissivity for different wavelengths; the data in Fig. 3 is calculated from the equation [2]:

$$T_{reported}^{-1} = T_{actual}^{-1} - \left(\frac{\lambda}{c_2}\right)\cdot \ln\left(\frac{\varepsilon_{actual}}{\varepsilon_{assumed}}\right)$$

where $T_{reported}$ and $T_{actual}$ are the temperature reported by the instrument and the true target temperature in Kelvin. Lambda ($\lambda$) is the measurement wavelength in microns, $c_2$ is the second Planck radiation constant (14,388 micron·Kelvin), $\varepsilon_{actual}$ is the correct target emittance, and $\varepsilon_{assumed}$ is the emittance entered into the instrument. The math is more complex, but a similar effect occurs for dual wavelength measurements.

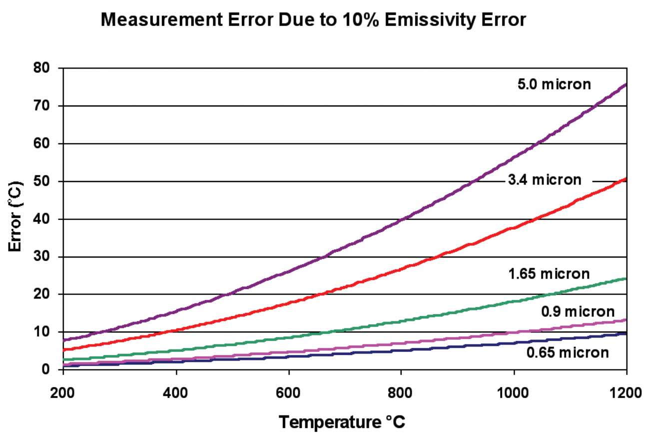



*Figure 3: Emissivity errors vs. temperature for several different wavelengths. Error increases nearly proportionally with measurement wavelength.*

In addition to reducing the errors due to emissivity, short wavelength instruments provide much better resolution. At short wavelengths, the increase in light energy per degree temperature is greater, making it easier for the instrument to detect a small change in temperature.

Short measurement wavelength instruments have generally had two limitations. The large change in signal for a given change in temperature limits the breadth of the measurement range, and the very small emission from low temperature targets at short wavelengths limits the ability to measure relatively low temperatures.

New classes of instruments that make use of the advancements in microelectronic circuits have been developed. These instruments address both of these limitations, and provide additional improvements in repeatability, speed, and configurability.

## Advanced Circuit Design

In the past, optical pyrometers measured light energy via a photodiode sensitive to a particular range of wavelengths, amplified the signal via hard wired amplifiers, and provided a calibrated output of temperature. Amplification was through one of three techniques:

1. Single Linear Amplifier: Provides very good resolution but extremely narrow measurement range and susceptible to circuit noise at low measurement temperatures.
2. Logarithmic Amplifier: Provides larger measurement range but has reduced resolution and is susceptible to circuit noise at low measurement temperatures.
3. Multiple Linear Amplifiers with automated amplifier switching: Provides good resolution and broader range but is susceptible to circuit noise at low measurement temperatures.

Advancements in microelectronic circuits allow for the vast majority of the amplification and measurement circuitry to be brought onto a single chip. This type of circuit design provides significant improvements in range, resolution, and repeatability. Additionally, microprocessor control of the measurement chip allows for broadening of the range via automatic signal averaging at lower temperatures. The microprocessor can also improve repeatability through more sophisticated compensation for changes in ambient temperature.

### Range

All optical pyrometers work under the same general principles and therefore have similar tendencies regarding range. Modifying the optics to increase or decrease the amount of light reaching the photodiode shifts the range; the top of the range shifts significantly compared to the bottom. Figure 4 shows the change in diode current for a 900nm instrument vs. temperature over a 275 – 2200°C measurement range. The graph has been normalized so data from both lightpipe and lens based sensors could be included. Figure 6a and 6b show the new electronics configured with lens optics and lightpipe optics.

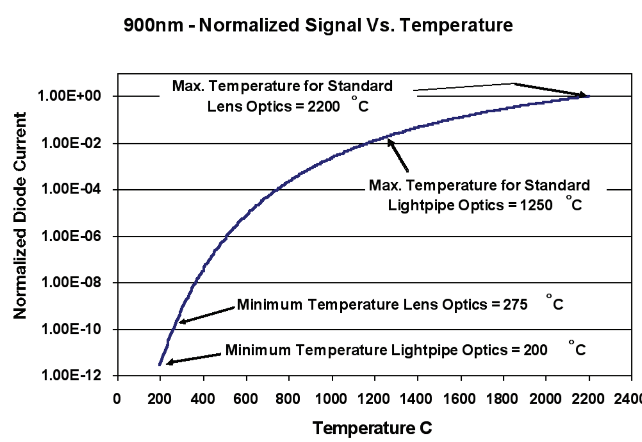



*Figure 4: Measurement ranges using broad light gathering lightpipe sensors or restrictive lens based sensors. The lightpipes allow lower temperatures but the lens systems provide greater breadth of range.*

A broad dynamic range can provide better control during process ramp up, thus maximizing process throughput or speeding process startup. Table 1 shows measurement ranges for several 1.6 micron wavelength industrial pyrometers from major manufacturers compared to the ranges available from instruments using advanced microprocessor based designs.

*Table 1: Comparison of temperature ranges between conventional pyrometers and the new design at the common 1.6um measurement wavelength. The new design allows a much lower minimum temperature on standard optics and an extremely broad range when restricted optics are used.*

| Temperature Ranges Using 1.6 um Wavelength | |
|---|---|
| Manufacturer A | 250 – 1000°C (482 – 1832°F)<br>350 – 2000°C (662 – 3632°F) |
| Manufacturer B | 300 – 1300°C (572 – 2372°F) |
| Manufacturer C | 250 – 1000°C (482 – 1832°F<br>350 – 2000°C (662 – 3632°F) |
| New Instrument Standard Range Lens Optics - D/40 | 65 – 1100°C (149 – 2012°F) |
| New Instrument Expanded Range Lens Optics – D/400 | 125 – 2800°C (257 – 5072°F) |

**Resolution**

Resolution is generally described as the ability to detect a change in reading that can be differentiated from instrument noise. As pyrometers approach the bottom of their measurement range, resolution degrades. Many instruments define the bottom end of their range as the temperature where resolution is 1°C at one measurement update per second. Table 2 shows how the resolution of the new instrument changes with temperature and output rate.

*Table 2: Measurement resolution vs. measurement rate and temperature.*

| Low-Temp Range Pyrometer 1600nm (65 - 1100°C) | 1 reading per second | 10 readings per second | 100 readings per second | 1000 readings per second |
|---|---|---|---|---|
| 1.0°C Resolution | 65°C | 80°C | 108°C | 148°C |
| 0.1°C Resolution | 102°C | 125°C | 154°C | 201°C |
| 0.01°C Resolution | 146°C | 175°C | 215°C | 275°C |

Better resolution from a process instrument can improve the process control capability. Depending on the thermal characteristics of the process, a process that can measured with a 0.01°C resolution, can be controlled to 0.1°C or better. Tighter temperature control can significantly reduce process variation.

**Repeatability**

Repeatability defines the ability of an instrument to provide an identical measurement when measuring the same signal, in this case, temperature. In general, there are two primary sources of drift that can affect an optical pyrometer, these are:

- Time based drift, usually given in °C per year, which accounts for changes in calibration of the photodiode measurement and amplification circuit. Time based drift specifications for pyrometers are typically 2°C/per year
- Ambient temperature changes affecting the photodiode measurement and amplification circuit as well as shifting the spectral response of the photodiode or optical filters. Typical specifications for ambient temperature drift range between 0.15 and 0.35°C per °C change in ambient temperature.

Tests at elevated ambient temperatures (80 – 85°C) over a two year period have shown the microprocessor based measurement circuit to be significantly less sensitive to time based drift. Drift of less than 0.1°C per year is expected throughout the range of the instrument. The microprocessor monitors the electronics temperature and automatically compensates for the spectral shift of the photodiode; less than 0.05°C/°C change in ambient temperature is expected.

## Applications

The driving force behind the development of this new instrument was the need for better optical temperature measurement instruments in semiconductor processes, particularly lamp heated Rapid Thermal Processing (RTP) chambers. Figure 5 shows how silicon wafers become transparent at wavelengths above 1.0 micron [3].

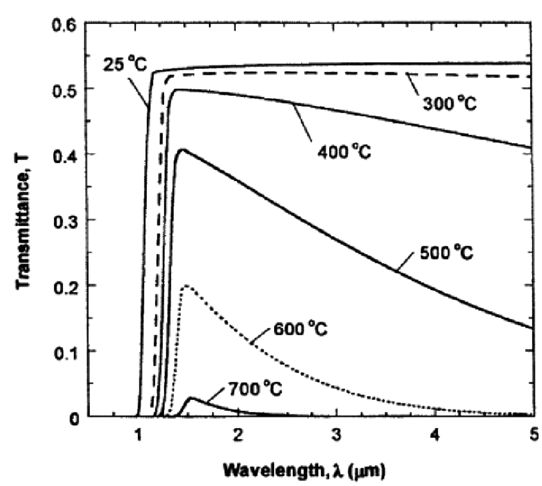



*Figure 5: Silicon wafer transmission vs. wavelength and temperature. The transmission at long wavelengths make short wavelength measurements essential.*

Pyrometer measurements of partially transparent materials are very difficult, particularly when the transmission is a strong function of temperature, or when there are other sources of infrared radiation transmitting through the target surface. If transparency issues rule out long wavelength measurements, then the ability to measure lower temperatures using short wavelengths becomes critical.

Recently, the new instrument has been used in a number of non-semiconductor processes, including induction heating, graphitization, and specialty glass measurements. Two types of measurements are described, rapid induction heating and plasma processing; these processes are of interest as they highlight the unique properties of the instrument. The plasma measurements were made in a semiconductor process but are equally applicable to any plasma process in which the target is heated above 100°C and the infrared emission from the plasma is not more than 50 times greater than the infrared emitted from the target, plasma nitriding for example.

**Rapid Induction Heating**

Induction heating systems can heat samples to high temperatures very quickly. In some applications the heating rate can be so rapid that it cannot be controlled with conventional temperature control systems. The instrument has been used to measure several inductively heated processes with no significant effects from the induction field observed.

The instrument can be configured with different measurement optics to optimize the measurement. Figure 6a shows the instrument configured with conventional lens optics, Fig. 6b shows the instrument configured with lightpipe optics. Lightpipe sensors are used to measure in close proximity to targets, they are manufactured from transparent single crystal materials and can withstand heating to over 1500°C. Lightpipes can be built directly into the induction heating hardware. Either the lightpipe or the lens optics can be coupled to a fiber-optic cables to minimize sensor size or if the environment is too harsh for the electronics.

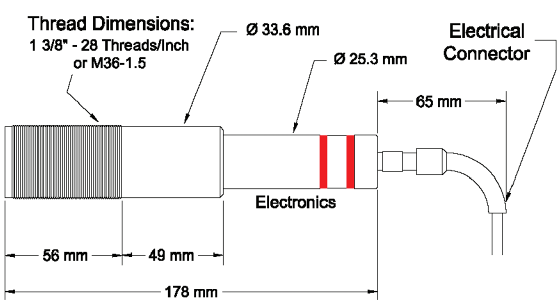



*Figure 6a: Lens optics for measurement of targets a few inches to several feet from the instrument.*

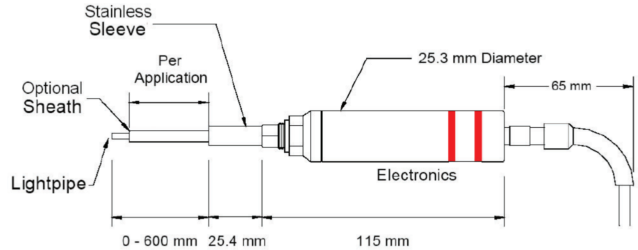



*Figure 6b: Lightpipe optics for close proximity measurements. Lightpipes measure with wide optical cone angles but can be apertured down to restrict view angle. Lightpipes are small diameter crystaline rods which act as very high temperature fiber-optic conduits of light to the electronics.*

Through the upper 85% of its range, the new instrument provides measurement rates as fast as 1000 readings per second. The minimum and maximum temperature that a given instrument can measure will depend on the optics and measurement wavelength configuration of the instrument. Tables 3a and 3b provide range and speed data for lightpipe and lens optics for 900nm and 1600nm instruments.

*Table 3a: Temperature ranges for different optics and 900nm measurement wavelength.*

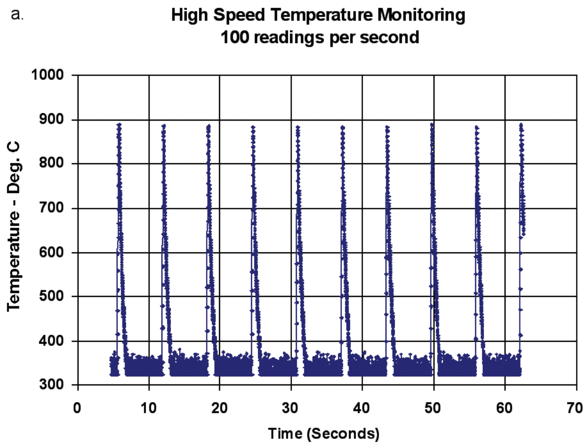
| 900 nm Wavelength | Lightpipe Optics | Lens Optics (D/40) |
|---|---|---|
| Complete Range | 215 – 1250°C | 275 - 2150°C |
| 100 readings/second | 305 - 1250°C | 390 - 2150°C |
| 1000 readings/second | 365 - 1250°C | 470 - 2150°C |

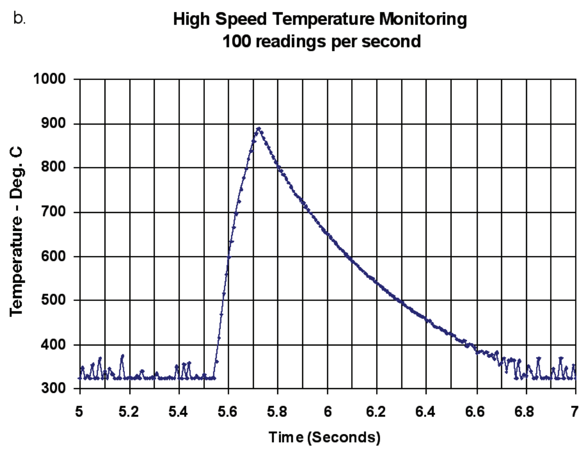
*Table 3b: Temperature ranges for different optics and 1600nm measurement wavelength.*

| 1600 nm Wavelength | Lightpipe Optics | Lens Optics (D/40) |
|---|---|---|
| Complete Range | 30 - 670°C | 65 - 1100°C |
| 100 readings/second | 55 - 670°C | 110 - 1100°C |
| 1000 readings/second | 85 - 670°C | 150 - 1100°C |

Lightpipe and lens based instruments can be apertured to reduce the amount of light received from a given target temperature. Aperturing increases both the minimum and maximum temperatures; the maximum temperature increases more, so the overall measurement range of the instrument increases.

Figures 7a and 7b show measurements of a small resistively heated sample with a measurement rate of 100 readings per second.




*Figures 7-a and 7-b: Data from a high speed heating process. Sample is heated with a known power input from ambient to 900°C in 0.18 seconds. Top graph shows several repeat runs, bottom graph shows the first run expanded.*

Data may be polled from the probe using either Modbus protocol or received in a streaming mode at rates of 1000 readings per second in real time. The measurements can be used to indicate a set temperature has been reached or as part of a closed loop control scheme. Recent experiments have been run which demonstrate the capability of the probe to provide feedback to a high speed PID control program, controlling large temperature changes at ramp rates in excess of 3000°C per second with less than 5°C overshoot.

## Subtraction of Background Plasma Radiation

Plasma processing is commonly used in semiconductor wafer processing for both deposition and etch processes. Temperature measurements in plasma chambers are often difficult; electromagnetic interference from the plasma can interfere with thermocouple measurements, and infrared emission from the plasma can overwhelm the infrared emitted from the target.

Subtraction of background radiation has been used before in optical temperature measurements. The digital nature of the new instrument described simplifies the subtraction process and increases the amount of background radiation that can be successfully subtracted. Figure 8 below shows the diode current resolution of the new instrument when measuring the signal from a light emitting diode at 50 readings per second. The Y-axis of the graph is the photodiode current measured by the instrument and is what the subtraction is based on. As the graph shows, the light intensity can be measured with up to five significant figures of resolution. This level of resolution allows for meaningful subtraction of very high levels of background radiation

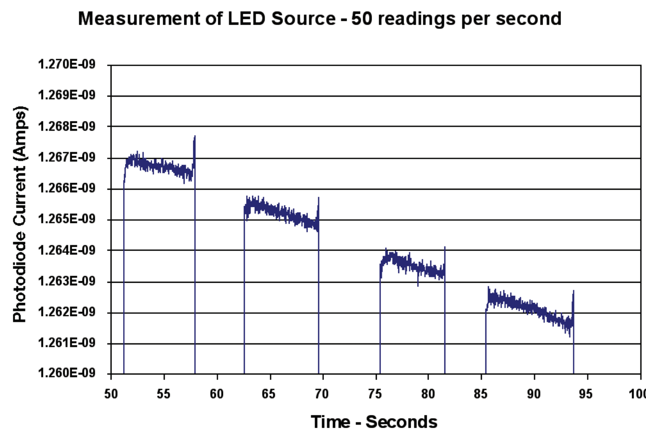



*Figure 8: Measurement of an LED light source. Photodiode current is a measure of light energy received by the probe. This is the current used in the subtraction algorithm described.*

Figure 9 shows a semiconductor plasma etch process in which a lightpipe sensor is used to measure the back of a wafer. The process temperature is below 200°C, requiring a measurement wavelength of 1600nm. At 1600nm, the wafer is semi-transparent, allowing the plasma radiation to transmit through the wafer and become part of the measurement.

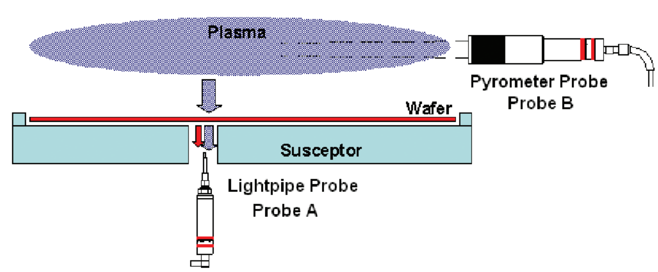



*Figure 9: Diagram of a plasma process being measured by two probes. Bottom probe measures wafer but is influenced by the radiation from the plasma. Side probe measures plasma only. Photodiode current from side probe is used to determine amount of current to be subtracted from bottom probe signal. The resulting current is then used to determine wafer temperature.*

The equation used for the subtraction is as follows:

$$I_V = I_A - b \cdot I_B$$

where $I_A$ is the current measured by the sensor aimed at the target (Probe A in Fig. 9), $I_B$ is the current measured by the sensor measuring the background signal (Probe B). The software allows the multiplier term 'b' to be varied as a function of the magnitude of $I_B$. Temperature is calculated from $I_V$ using the same current-to-temperature relationship developed during the calibration of Probe A. Any adjustments to the target emissivity are divided into the $I_V$ current prior to the calculation of target temperature.

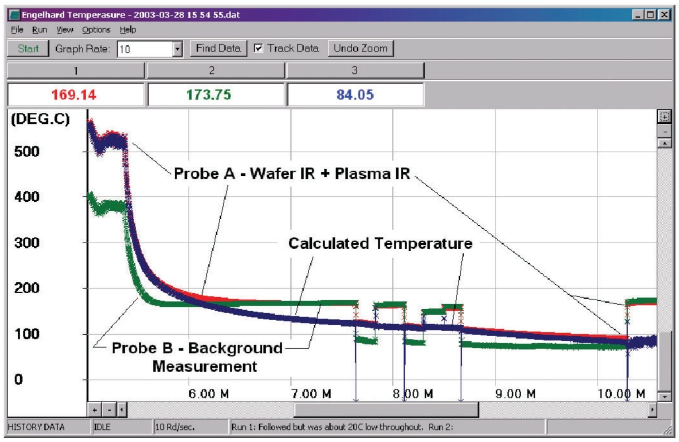



*Figure 10: Measurement results shown with graphical software tailored for interface with instrument.*

Figure 10 shows the three resulting temperature measurements. The red data points are from Probe A – Wafer IR + Plasma IR, the green data points are from Probe B – Background Measurement. The blue data points are the 'virtual' measurement, marked Calculated Temperature in Fig. 10. The Calculated Temperature is based on the results of the subtraction calculation. The process cycle starts with a combination of heating lamps and plasma. When the wafer has been heated, the lamps are shut off (t = 5.5min) and the wafer begins to cool. At 7.5 minutes, the plasma power is cycled on and off, or the power changed, several times. Note that when the plasma is turned off, the green graph line (Probe B) drops to very low values and the red line (Probe A) drops to equal the blue line (Calculated Temperature). With the plasma off, there is nothing to subtract so there is no effect on the measured temperature and Probe A and the calculated temperature overlap.

At the end of the run, the wafer has cooled to less than 100°C and the plasma is turned back on. At this point, the IR intensity from the plasma is over 100 times greater than the IR from the wafer, yet a successful calculation of temperature is still made.

## Conclusions

New electronics have been developed for measuring short wavelength infrared radiation for the purpose of determining the temperature of the body emitting the IR radiation. The new electronics allow for a broader measurement range, higher resolution, and greater repeatability than conventional IR temperature instruments. The high speed, short measurement wavelengths, and resolution of the instrument make it particularly well suited for measurement of induction heated processes and processes in which high levels of background radiation needs to be subtracted from the measurement.

Visit www.catalysts.basf.com for more information. BASF's Catalysts division offers exceptional expertise in the development of technologies that protect the air we breathe, produce the fuels that power our world and ensure efficient production of a wide variety of chemicals, plastics, adsorbents and other products.

## References

1. Schietinger C, Adams B, *In-Situ Optical Wafer Temperature Measurement*, 8th Symposium on Temperature, October 2002.
2. D. DeWitt and G. Nutter, Theory and Practice of Radiation Thermometry, Chapter 6, John Wiley & Sons, New York (1988).
3. Z.M. Zhang, B.J. Lee, and H.J. Lee, *Study of the Radiative Properties of Silicon-Based Materials for Thermal Processing and Control*, 11th IEEE International Conference on Advanced Thermal Processing of Semiconductors – RTP2003, September 2003.



BASF

The Chemical Company