In Situ Calibration of Lightpipe Radiometers for Rapid Thermal Processing between 300 °C to 700 °C

W. A. Kimes[1], K. G. Kreider[1], D. C. Ripple[1], B. K. Tsai[2]

[1]Process Measurements Division, [2]Optical Technology Division
National Institute of Standards and Technology
100 Bureau Drive
Gaithersburg, MD 20899

Many Rapid Thermal Processing (RTP) tools are currently monitored and controlled with lightpipe radiometers (LPRTs), which have been limited to measuring temperatures above 500 °C because of the low signal level below 500 °C. New commercial LPRTs couple the optical detector directly to the lightpipe, eliminating the signal loss from optical cables. These cable-less light pipe radiometers (CLRTs) are capable of measuring temperature below 300 °C. We present the results of calibrating a CLRT against our NIST thin-film thermocouple (TFTC) calibration wafer from 315 °C to 700 °C in our NIST RTP test bed. Below 550 °C, light leakage from the heating lamps of the RTP tool introduced a significant error in the LPRT readings. By measuring the transient response of the LPRTs following rapid energizing of the heating lamps, we were able to differentiate between the radiance of the wafer and ambient chamber light. This allowed us to correct for the ambient chamber light from the radiance of the wafer.

INTRODUCTION

Lightipe Radiometers (LPRTs) are used in many Rapid Thermal Processing (RTP) tools to monitor the temperature of a silicon wafer. Previous LPRT designs have been limited to temperatures above 500 °C due to the low signal levels. Improvements in the design of the optical detector of the LPRT have decreased the detector size. This reduction in size allows it to be mounted directly onto the lightpipe thus eliminating the need for an optical cable. The new cable-less lightpipe radiometers have made it possible to measure wafer temperature below 300 °C. As the wafer temperature decreases, ambient light in the chamber generates an increasing error in the temperatures measured by the cable-less lightpipe radiometer (CLRT). A change in wafer temperature from 500 °C to 300 °C decreases the signal level by a factor of approximately 1200. Thus even a small light leak can generate significant errors at low temperatures. As the temperature of interest decreases it becomes increasingly important to have an *in situ* calibration of the CLRTs used to monitor the wafer. Presented here are the results of two calibration methods used to calibrate the CLRT using a NIST thin-film calibration wafer from 315 °C to 700 °C. The first method is a direct comparison of the CLRT with a NIST thin-film instrumented wafer. The second is a modified comparison between the NIST calibration wafer and the CLRT, where the ambient light is subtracted from the measured CLRT signal.

Existing methods of determining the lamp signal either involve two LPRTs or use of the ripple technique [1]. For the commercial CLRT used in this study, the sample rate was 5 measurements a second, which is too slow for use of the ripple technique.

EXPERIMENT

The CLRT consisted of a 2 mm diameter lightpipe with a 4.5 mm diameter sheath surrounding it. The photodetector and associated electronics were located at the end of the lightpipe. The CLRT was set to take 5 measurements per second. The lightpipe was calibrated against a NIST cesium heat-pipe blackbody. The heat pipe blackbody was monitored using a Au/Pt thermocouple. A similar calibration, using a NIST sodium heat-pipe blackbody, is described in ref. 2. The CLRT was capable of giving readings both in temperature and in photocurrent generated by the photodetector. This current is directly proportional to intensity of light at a wavelength of 950 nm.

We used two NIST thin-film thermocouple wafers for calibration of the CLRTs. Both these wafers had a 700 nm oxide layer and were instrumented with Rh and Pt thin films (Fig. 1). The wafer emissivity at 950 nm wavelength was near 0.67 at 300 °C and 0.65 at 700 °C. Each wafer had two thin-film thermocouple junctions near the center, at 5 mm and 15 mm from the center, and two junctions at the mid-radius, 50 mm from the edge of the wafer. These wafers had Pt/Pd wire thermocouples welded to the Rh leg of the thin-film differential thermocouples, and Pt wires welded to the Pt leg of the thin film thermocouples.

Figure 1. A photograph of a Pt/Rh thin-film thermocouple wafer used in the calibration.

The method of calibration of the TFTCs has been described in detail previously [3]. Thin-film thermoelement test samples were sputter deposited simultaneously with the calibration wafer. These 10 mm by 50 mm silicon wafer samples were calibrated by comparison with calibrated Pt/Pd wire thermocouples. A fused-silica tube furnace was used for calibration of the thin-film thermoelements on the test samples versus pure Pt wire up to 1000 °C. The tests for specimens reported in this paper were run in N_2 with up to 0.0001 mole fraction O_2. A water-cooled copper clamp holds one side of the test sample. This clamp is inserted into the tube furnace to heat the measuring junction while the reference junction is water-cooled. The Pt leads of the Pt/Pd thermocouples were also used to determine the emf of the thermoelectric film generated by the difference in temperature between the reference junction and measuring junction. The total combined uncertainty of the NIST test wafer for use in the calibration of the low temperature lightpipe was 1.5 °C (*k*=1).

The output of each thermocouple was measured with an 8-½ digit digital multimeter with an expanded uncertainty (*k*=2) of 0.3 µV. The thermocouple and thin-film emf values were measured sequentially through a scanner. A complete measurement cycle, measuring two thermocouples and four thin-film thermocouples, took approximately one minute to complete. Both the scanner and multimeter were controlled using a custom computer program.

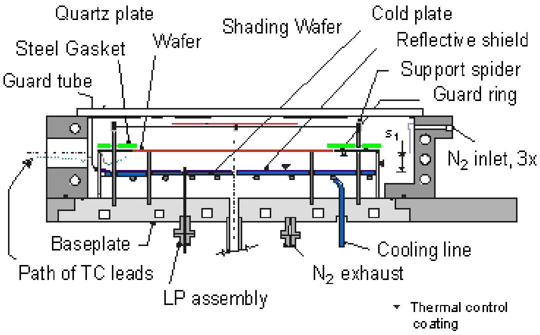

Figure 2. Diagram of the NIST RTP test bed.

The wafer was heated using the NIST RTP test bed. The NIST RTP test bed (Fig. 1) has been used to simulate RTP tool temperature measurements and for LPRT *in situ* calibration using thermocouple wafers. A bank of 24 two-kilowatt quartz infrared halogen lamps with a cold, highly reflective chamber (not shown in the figure) is used to heat the wafer. The lamps heated the side of the wafer opposite the thin films. The base plate and chamber walls were water cooled. The test wafer was supported by alumina pins 10 mm above the reflective shield (95.5 % reflectivity). A Pt-coated silica-glass guard tube rests on the RTP base plate and surrounds the reflecting shield. Resting on the guard tube, at the same height as the wafer, is a Pt-coated silica-glass guard ring. The Pt-coated guard ring had a 300 mm outer diameter and a 202 mm inner diameter. The guard ring, guard tube, reflecting shield and wafer form a reflecting cavity for the CLRT. The tip of the CLRT is placed flush with the reflecting shield at the center of the test wafer. The wires from the test wafer were taken outside of the reflective cavity by a 2.5 cm by 1.3 cm rectangular notch in the guard tube. This notch was shaded from the heating lamps by the guard ring. We used a shading wafer, 150 mm in diameter, to reduce the thermal gradients across the test wafer. This shading wafer was 25 mm above the test wafer, below the fused quartz plate that separates the light box from the test chamber. All tests were run in a purged atmosphere of N_2 with up to 0.1 mL/L O_2.

Two modifications were made to the RTP chamber in order to reduce radiation from the heating lamps entering the reflecting chamber made by the test wafer, reflecting shield, guard ring and guard tube. First, the notch in the guard ring, where the wires were taken out of the reflecting cavity, was covered with aluminum foil. Second, a 2 mm thick stainless steel gasket with an outer diameter of 300 mm and an inner diameter of 196 mm was placed on top of the wafer and guard ring. Thinner gaskets tended to warp excessively. The gasket was designed to overlap the gap between the test wafer and guard ring.

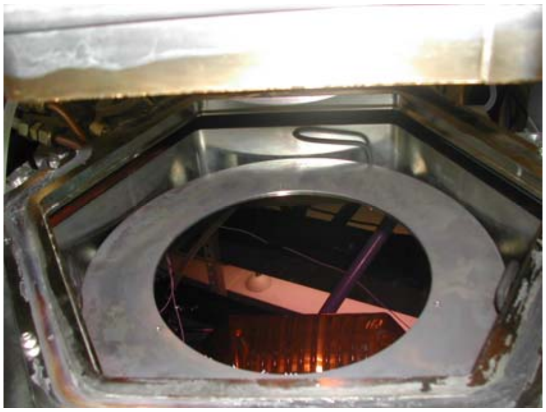

Figure 3. A picture of the NIST RTP test bed with the test wafer installed. The heating lamp housing unit is reflected by the test wafer. The shading wafer was removed in order to allow easy viewing of the stainless steel gasket resting on top of the wafer.

To study the sensitivity of the measurements to light leakage, ceramic spacers were used to lift the stainless steel gasket away from the wafer and reflecting shield. This had the effect of increasing the ambient radiation in the reflecting chamber, radiation not due to Planck radiation of the test wafer. Tests were performed with 6 mm spacers, 2.5 mm spacers, and no spacers.

RESULTS

Figure 4 depicts the difference in indicated temperature as measured by the TFTC and the CLRT. The CLRT read colder than the thermocouples by 2.5 °C until the wafer temperature dropped below 500 °C. Once the wafer was below 500 °C the difference between the CLRT and the TFTC increased inversely with temperature, with the CLRT reading higher than the TFTC. With no ceramic gasket spacers the difference between the TFTC and CLRT was 20 °C at 320 °C. With a 6 mm ceramic spacer the difference between the TFTC and CLRT was 52 °C. Below 500 °C the difference between the temperature as measured by the TFTC and the CLRT was due to radiation, other than that generated by the wafer, entering into the CLRT. The large majority of this unwanted ambient radiation was due to light from the heating lamps entering the reflecting cavity.

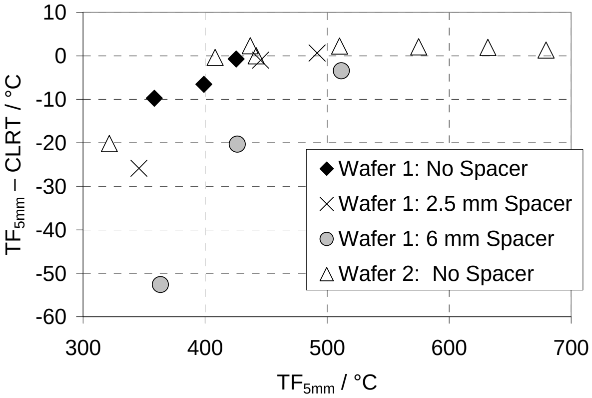

Figure 4. Plot showing the indicated temperature difference between the lightpipe and the thin-film thermocouple junction. Error bars represent the combined uncertainty of the measurement of the wafer temperature by the TFTC and the CLRT.

Measurements taken with no ceramic gasket spacers showed that the light leakage was reproducible to within the measurement uncertainties between runs and wafers with identical spacer configurations. This reproducibility allowed a calibration of the CLRTs by the thermocouple wafer with an uncertainty of 1.5 °C (k=1) for the gasket setup with no ceramic spacers. This uncertainty is the combined uncertainty of the CLRT repeatability, the calibration and measurements of the thermocouples and the uncertainty associated with the difference in measurement locations of the lightpipe and thin-film thermocouples [3].

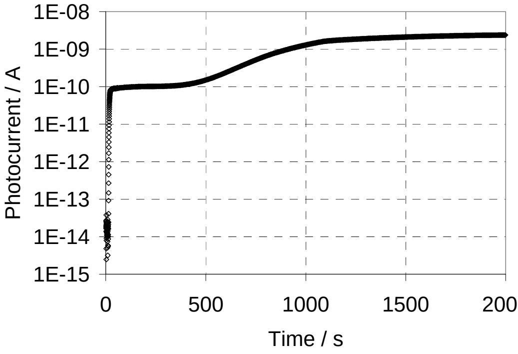

Figure 5. A typical heating cycle of the test wafer as measured by the CLRT.

A typical plot of photocurrent versus time during a wafer heat-up cycle is shown in Fig. 5. In a given heating cycle, from room temperature to the measured, warmed steady-state temperature, the CLRT measured two plateaus. The initial plateau occurred much faster than the increase in wafer temperature, as measured by the thin-film thermocouples. This indicated that the initial plateau was due to ambient radiation. The time constant associated with the heat up into the initial plateau was slower than would be expected for a tungsten filament used in the halogen heating lamps. It is unlikely the ambient radiation originates from the guard ring or guard tube, both because of their proximity to the water-cooled walls of the chamber and because their large thermal mass would force their respective heating rates to be slower then the test wafer. It is most likely that the ambient radiation originates from radiance of both the fused-silica tubes that house the halogen lamps and the fused-silica plate between the lamps and the wafer.

ANALYSIS

In the absence of light leakage and for a CLRT calibrated against a blackbody reference source, a wafer temperature as measured with the CLRT is expected to be slightly lower than actual wafer temperature due to the reflecting cavity beneath the wafer having an emissivity slightly less than unity. Previous work in the range 600 °C to 900 °C [4] has shown that the difference between temperatures indicated by the CLRT and the thermocouple wafer varies only slowly with temperature. Measurements on the emissivity of silicon with an oxide layer have shown that there is little change in the emissivity from 300 °C to 700 °C [4], so the sharp increase in CLRT readings relative to the thermocouple readings below 500 °C cannot be attributed to changes in wafer emissivity.

To test our understanding of the CLRT response, we have corrected the CLRT readings for leakage of ambient light. In order to determine whether or not the ambient radiation was a constant during a heating cycle we subtracted the predicted photocurrent produced by Planck radiation of the wafer itself at a given temperature, as measured by the thermocouples, from the total measured photocurrent. For the sake of determining the predicted photocurrent of the wafer it was assumed that the effective emissivity of the wafer was both a constant and one. Previous models [5] have shown the effective emissivity of the reflecting chamber in our RTP test bed is close to one.

Rather than using a theoretical expression for the relation between photocurrent and wafer temperature, we relied on the calibration table of the actual CLRT in use. This approach includes instrumental effects in the CLRT response that would be neglected otherwise. The calibration table had an entry every 5 °C. A logarithmic interpolation was used to determine the photocurrent of wafer temperatures between table entries. The predicted wafer photocurrent was then subtracted from the total measured photocurrent. Results of this correction process are depicted in Fig. 6.

Table 1. Calibration table for CLRT.

Temperature / °C	Photocurrent / A
400	$6.26\text{x}10^{-10}$
405	$7.44\text{x}10^{-10}$
410	$8.80\text{x}10^{-10}$
415	$1.04\text{x}10^{-9}$
420	$1.23\text{x}10^{-9}$

Fluctuations in the photocurrent from the ambient radiation in the chamber were constant to within 2×10^{-11} A while the wafer was at approximately 350 °C (with a photocurrent of $9.67\text{x}10^{-11}$ A). The fluctuations in photocurrent increase rapidly with temperature to 1×10^{-9} A at 650 °C (photocurrent of $3.65\text{x}10^{-7}$ A).

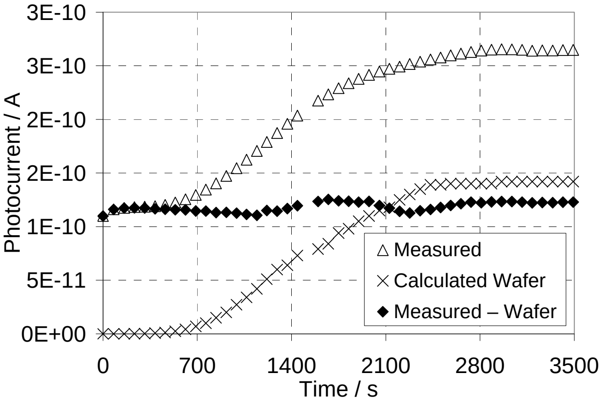

Figure 6. A plot depicting the measured photocurrent, the calculated effective photocurrent of the wafer and the difference between the total measured photocurrent and the effective wafer photocurrent.

In order to determine the magnitude of the ambient radiation we used a point in the middle of the initial plateau of the photocurrent versus time plot as measured by the CLRT. This value was then subtracted from the value of the second plateau. The value of the second plateau was determined by using the final measurement taken before the wafer began to cool off. This final, corrected photocurrent was then converted to temperature using the calibration table mentioned earlier. The results of this correction technique can be seen in Fig. 6.

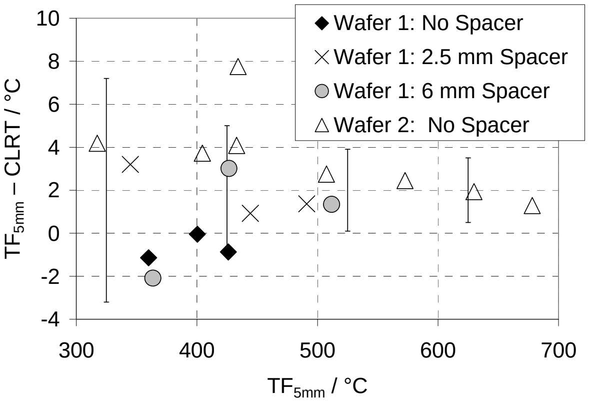

Figure 7. Adjusted calibration of the CLRT.

The added uncertainty of the correction factor, 2×10^{-11} A to 1×10^{-9} A in photocurrent, translates to a 5 °C uncertainty in the CLRT temperature measurement at 300 °C. This uncertainty diminishes with an increase in wafer temperature, such that at 600 °C this uncertainty component in temperature was less than 0.1 °C. The uncertainty of the thermocouple measurements was 1.5 °C. The manufacturer's stated repeatability for the CLRT was 0.15 °C. The total uncertainty of the calibration, with the correction applied for ambient chamber light, is shown in Table 2.

Table 2. Total uncertainties for the adjusted calibration of the CLRT.

Wafer Temperature /°C	u (k=1) / °C
325	5.2
425	3.0
525	1.9
625	1.5

As expected, the corrected CLRT readings are lower than the thermocouple wafer readings by a few degrees Celsius, and this offset varies slowly with temperature.

CONCLUSIONS

Using the NIST thin-film thermocouple wafer we were able to calibrate the CLRT in situ on the ITS-90 with an uncertainty below 2 °C for temperatures above 300 °C. This uncertainty was dependent on the reproducibility of the ambient radiation. The dominant term in the uncertainty of the CLRT calibration was the uncertainty of wafer temperature as measured by the TFTC.

We developed a method to compensate for the ambient radiation detected by the CLRT. By monitoring the photocurrent generated by the CLRT during the energization of the heating lamps we were able to measure the ambient radiation in the reflecting chamber. Subtracting the initial photocurrent measured on lamp energization from the total measured photocurrent successfully compensated for the ambient radiation. Calibrations performed using the compensation method had uncertainties as high as 5.2 °C at 325 °C. This increase in uncertainty was due to the fluctuation in ambient radiation during a given heating cycle. These fluctuations could be minimized by using a constant voltage source in the power supply used for the heating lamps.

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