CALIBRATION OF A LOW-TEMPERATURE CABLE-LESS LIGHTPIPE PYROMETER ON THE NIST POST-EXPOSURE BAKE TEST BED

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The advent of the cable-less lightpipe radiation thermometer (CLRT) has resulted in a significant improvement in the accuracy of lightpipe radiation thermometer calibrations and measurements. CLRT systems show great promise in noncontact measurements by the elimination of the uncertainties caused by the long fiber optic cables and their connections and by the extension of the spectral range to handle low-temperature applications down to room temperature. A CLRT was first calibrated with the oil-bath and water-bath blackbody sources from 40 ºC to 180 ºC. Then the CLRT was compared to thin-film thermocouples and platinum resistance thermometers on a silicon wafer heated in a Post-Exposure Bake (PEB) Test Bed. Comparison of the CLRT with both the blackbody and thermocouple standards provides confidence in using CLRTs and allows researchers to continue research into improving the accuracy and feasibility of applying CLRTs in semiconductor processing.

INTRODUCTION

During the past decade, significant advancements in the research of lightpipe radiation thermometers (LPRTs) at the National Institute of Standards and Technology (NIST) have improved the calibration, application, quality control, and analysis of LPRTs in the field of Rapid Thermal Processing (RTP) [1-6]. Recently the development of cable-less lightpipe radiation thermometers (CLRTs) has aided in the improvement of temperature accuracy in RTP applications by eliminating the uncertainties caused by the fiber optic connections [6]. Until recently, the temperature range of research at NIST has been between 600 ºC and 1000 ºC. In the last few years, there has been increased interest and need for investigating lower temperatures.

The use of any type of radiation thermometer at low temperatures (around 100 ºC) is more challenging than at higher temperatures (above 600 ºC) for several reasons. First, thermal infrared background from ambient sources contributes more to the temperature error as the target temperature approaches the ambient temperature. This background has to be minimized or dealt with in the data analysis. Second, smaller signals and radiances at the lower temperatures require more effort to maintain a high signal-to-noise ratio. Third, lower temperatures often necessitate the use of infrared sensors, which often are more difficult to use than traditional silicon detectors for the higher temperatures. Infrared detectors are in general more spatially non-uniform, more non-linear, less sensitive, noisier, and exhibit more drift than silicon detectors. In addition, infrared detectors may require the use of cryogenic and vacuum equipment, thus adding to the complexity, cost, and level of effort needed to operate the detectors. These challenges emphasize the great need for more research to improve temperature measurements using infrared detectors.

CLRTs have recently been developed for applications at temperatures lower than those for RTP. One such application is the post-exposure bake (PEB) process, which consists of exposing process wafers to a set of controlled, steady-state temperature environments in order to polymerize the photoresist used in photolithography. Accurate temperature measurements enable the tight temperature control required in order to meet critical dimension budgets using chemically amplified resists employed in the 130 nm to 70 nm technologies [7]. Using commercial test wafers with resistance-type sensors [8], steady-state temperature measurements during calibration runs are reported to have an uncertainty of 20 mK in the range 15 °C to 230 °C (unless otherwise stated, all uncertainties in this document are given as standard uncertainties with coverage factor of $k = 1$ [9]). The possibility of using in situ lightpipe thermometers to maintain this precise temperature control would simplify PEB cures for photolithography by reducing the need for calibration runs.

This paper reports on the calibration of a CLRT using stable bath blackbody sources and on the measurement of a PEB test bed between 50 ºC and 150 ºC using the calibrated CLRT. The procedures, results, and uncertainties are discussed. Future work required for greater understanding of applying CLRTs in low temperature applications such as PEB is reviewed.

PROCEDURES

Before using the CLRT in the PEB test bed, two bath blackbody sources served as the reference sources for the calibration of the CLRT from 40 ºC to 180 ºC. The NIST water-bath blackbody (WBBB) with a calculated emissivity of 0.9997 ± 0.0003 [9] is the reference source for operating temperatures between 15 ºC and 70 ºC [10]. The NIST oil-bath blackbody (OBBB) is the reference source for operating temperatures between 70 ºC and 180 ºC [11]. The CLRT was first secured in an uncooled copper holder, which was mounted to a linear translation stage. The stage allowed for manual placement of the CLRT into the bath blackbody source for the calibration procedure. The lights in the laboratory were turned off to eliminate significant light leakage into the lateral side of the CLRT during measurement. When the CLRT was not being calibrated, the CLRT was translated away from the bath blackbody source along the linear stage. Data acquisition was performed by commercial software provided with the CLRT.

Comparisons were then made in the PEB test bed between CLRT readings and the readings of a silicon test wafer instrumented both with platinum resistance thermometers (PRTs) and wire and thin-film (TFTC) thermocouples. Our 200 mm test wafers were designed to have four pairs of corresponding TFTC junctions and matching commercial PRTs (see Fig. 1). The TFTC junctions are the obtuse and acute angles, and the PRTs are the double white spots. These sensor pairs were placed close to each other (6 mm to 7 mm) in order to measure the 200 mm wafer under nearly identical thermal conditions. In this paper, the PRT2 junction in Fig. 2 was situated 5 mm from the center, while the TFTC and PRT1 junctions were located 10 mm from the center. The dashed circle in Fig. 2 represents the spot size for the CLRT.

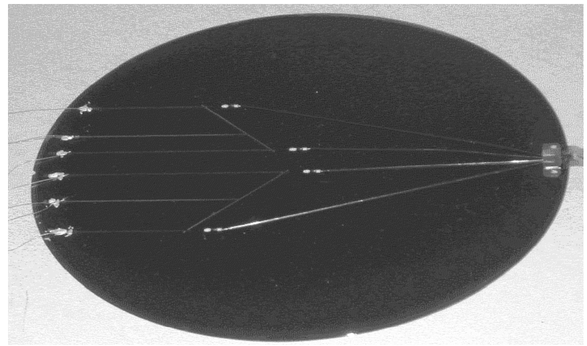

Figure 1. Wafer instrumented with PRTs and type E thin film thermocouples.

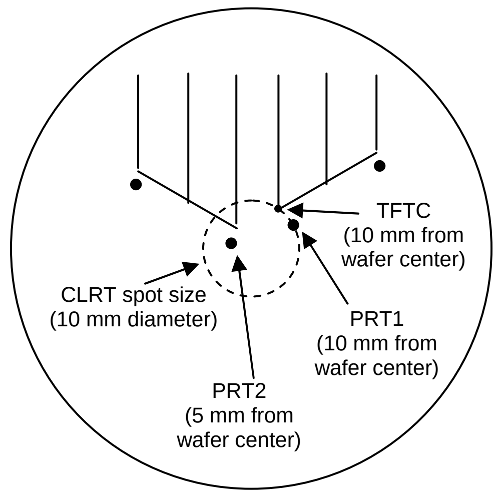

Figure 2. Layout for wafer PRT and type E thin film thermocouple junctions.

We designed and fabricated wafers with dual instrumentation. Our wafer had type E (Ni/Cr versus Cu/Ni) TFTCs on the wafer surface connected to calibrated type E wires, as well as a set of commercial embedded PRT sensors. Type E thermocouples have high output (50 μV/K to 70 μV/K) and permit lower measurement uncertainty at a high speed of data acquisition. The PRTs were embedded on 0.25 mm thick alumina substrates secured to the Si wafer with polyimide in a 2.74 mm by 1.43 mm oval shaped hole in the silicon. The PRT sensors were also covered with an AlN-filled polyimide and had 4-wire Pt foil leads. Fabrication of the dual-sensor test wafers started with a 200 mm Si wafer with a 690 nm thick thermal oxide. These wafers were sputter coated with the thin films of Ti bonded type E alloys (Ni-Cr and Cu-Ni). The TFTC wafer fabrication is described in more detail in references [12, 13]. For the PEB test wafers the connections between the matching thin films and thermocouple lead wires were made with silver epoxy on the bond pads of the wafer.

This design permits the metallurgically bonded TFTC junction to be essentially massless because it is 1 µm thick compared to the 0.76 mm thick wafer. We have measured the response times of the thin film junctions [14] and found them to be less than 5 ms. The TFTC is used as a differential thermocouple between the measuring junction and the interface with the wire thermocouple. We calibrated the thin-film thermocouples using the comparison method described in Ref. [15]. Because this temperature difference is less than 1 °C the measurement is not very sensitive to the calibration accuracy of the thin-film thermocouple. The wafers instrumented with both PRTs and TFTCs were designed to compare the transient response of the two types of sensors and not their absolute temperature measurement. In fact, the PRTs have smaller temperature measurement uncertainties than the thin-film thermocouples.

Because the silicon wafer is semitransparent for the lower temperatures at 1.6 µm, the operating wavelength of the CLRT, it was necessary to paint a 20-mm diameter spot on the back side of the wafer. The enamel paint was claimed to be stable up to 550 °C and had an emissivity of about 0.98 at 1.6 µm.

The PEB test module in Fig. 2 consisted of a stationary hot plate with moving placement pins and a hot plate cover, and a movable water-cooled chill plate. The hot plate cover moved vertically. The hot plate cover had a distance of 40 mm from the bottom of the cover to the hot plate when raised and 5 mm when closed. The hot plate was heated using 208 VAC with a zero-cross-firing SCR, which was controlled using a PID controller. The PID control system controlled the hot plate with a stability of ±1°C and had a temperature uniformity of better than 1.5 °C across the entire surface. The hot plate had six, 100 µm ±10µm high ceramic spacers, consisting of a 100 µm high base and a tapered ceramic retainer. The base of the spacers controlled the size of the air gap between the wafer and the hot or chill plate, thereby controlling heating or cooling of the wafer via thermal conduction through the gap.

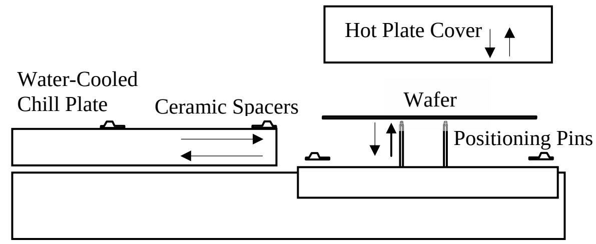

Figure 2. A diagram of the PEB test bed.

Two 8 1/2 digit multimeters were used to read the sensors on the specially instrumented test wafers. Each multimeter had an uncertainty of less then 0.5 µV for DC voltage measurements and 3 mΩ for the resistance measurements. The PRTs were read using a four-wire resistance measurement with a common current sink for all the sensors. The voltage from each wire thermocouple was read independently from the thin-film thermocouples. The cold junctions for the thermocouples were placed in glass tubes extending into a dewar filled with a shaved ice and distilled water slurry. Copper leads connected the cold junctions to the multimeter input terminals.

Comparison of the CLRT with the TFTC and PRTs were performed on the PEB test bed. The CLRT was placed in a vertical resting position into a stainless holder welded onto the top of the hot plate cover. A hole was drilled into the hot plate cover to allow the CLRT to view the silicon wafer. The tip of the CLRT was designed to be flush with the bottom of the hot plate cover. The TFTC wafer was instrumented as described above and then carefully placed into the wafer holder formed by the six ceramic spacers. Next, the hot plate was lowered to form a sealed chamber with the wafer and the rest of the chamber. The wafer was heated to the desired temperature. Finally, measurements were taken with the various sensors (CLRT, TFTC, and two PRTs).

RESULTS AND DISCUSSION

Calibration results for the CLRT using the NIST bath blackbody reference sources from 40 ºC to 180 ºC are shown in Fig. 3. Because the calibration offsets (blackbody temperature minus the CLRT temperature reading) are fairly linear with the blackbody temperature, a linear fit was performed and used for correcting the CLRT temperatures. The linear equation, $0.0155t + 0.6325$ (with a R^2 value of about 0.97), was used to calculate the offsets at each CLRT temperature reading t. This offset was then added to the CLRT temperature reading to obtain the corrected CLRT temperature.

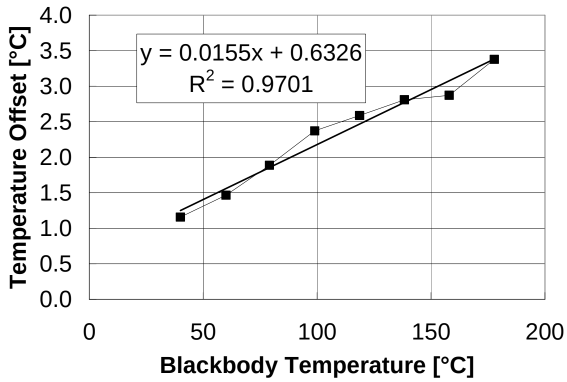

Figure 3. CLRT calibration offsets (and a linear fit) using the NIST bath blackbody sources from 40 ºC to 180 ºC.

The results from the contact sensors are shown in Table 1. All three sensors are within 1.2 ºC at 50 ºC and within 0.7 ºC for the two higher temperatures.

Table 1. Temperature measurements (ºC) from the TFTC, PRT1, and PRT2.

t, nominal	TFTC	PRT1	PRT2
50	48.3	49.4	49.5
100	98.0	98.2	98.5
150	147.2	147.2	147.7

The comparison of the contact sensors and the CLRT are shown in Table 2. Corrected CLRT temperatures in the third column are compared with TFTC temperatures in the second column. At 50 ºC, the corrected CLRT temperature is 0.7 ºC lower than the TFTC temperature, while the difference rises to 2.2 ºC at 150 ºC.

Table 2. Comparison of TFTC and corrected CLRT temperatures (ºC).

T, nominal	TFTC	CLRT	CLRT - TFTC
50	48.3	47.6	-0.7
100	98.0	95.3	-2.7
150	147.2	143.9	-2.3

Using commercial test wafers with resistance-type sensors, steady-state temperature measurements are reported to have an uncertainty of 20 mK in the range 15 °C to 230 °C [14]. The main contribution to the uncertainty of the TFTC measurements is from the Type E wire thermocouple and is approximately 0.1 ºC. The uncertainty of the CLRT measurements using the NIST blackbody source is 0.01 ºC at 40 ºC and 0.10 ºC at 140 ºC. In addition, the uncertainty due to the temperature gradients could contribute another 0.5 ºC at 150 ºC.

CONCLUSIONS

In this paper, we have demonstrated the feasibility of acquiring temperature measurements of a silicon wafer in a PEB test bed using a CLRT, a TFTC, and two PRT sensors. We have not established a complete uncertainty analysis in our results in this paper but are in fact currently evaluating uncertainties for the TFTC and CLRT sensors. The fact that the CLRT temperature is in some cases lower than the TFTC temperature by over 2 ºC needs to be investigated further. An uncertainty that needs further investigation is the temperature uniformity near the opaque spot and the lightpipe in the center of the wafer.

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