EFFECTS OF EXTRANEOUS RADIATION ON THE PERFORMANCE OF LIGHTPIPE RADIATION THERMOMETERS

C.W. Meyer

National Institute of Standards and Technology
Gaithersburg, Maryland, USA

ABSTRACT

Experiments were performed to study the influence of irradiation and heating of lightpipe radiation thermometers (LPRTs). LPRTs are currently the sensor of choice for temperature measurement in rapid thermal processing. Eight sheathed sapphire lightpipes from two separate manufacturers were used. The experiments demonstrated that the temperature of a lightpipe and the radiation surroundings can significantly affect the temperature displayed by an LPRT. The influence on the display temperature is much higher when the environment of the lightpipe is at a higher temperature than that of the surface being observed. Measurement uncertainty due to environmental influence can be minimized by calibrating the LPRT in an environment similar to that in which it will be used. The experiments showed that some lightpipes are less affected by their environment than others, suggesting that careful selection of lightpipes can also minimize the measurement uncertainty.

1. INTRODUCTION

Lightpipe radiation thermometers [1,2] (LPRTs) are becoming increasingly important as an industrial tool for temperature measurement, especially in the semiconductor industry [3-5]. LPRTs are composed of sapphire lightpipes that measure the radiance temperature of a nearby surface by collecting radiation at the tip of the LPRT and transmitting it through optical fibers to a photodetector. The simplest LPRTs only measure radiance temperature, so *in situ* calibrations and/or emissivity modeling must be made to relate this radiance temperature to the true surface temperature [6]. Other LPRTs use special techniques [3,7] to make measurements of the surface emissivity along with radiance temperature. Because the lightpipe acceptance angle is large (~45°), the tip is usually placed in close proximity (≈1 cm) to the target. LPRTs are currently the sensor system of choice for Rapid Thermal Processing (RTP) of semiconductors [5]. To meet the semiconductor industry requirements, RTP temperature measurement uncertainty of less than 2 °C at 1000 °C is needed [5]. Determination of the uncertainty of LPRT calibrations and measurements is therefore necessary. Calibration of an LPRT is usually performed by partially inserting it into a blackbody held at a constant temperature and comparing the LPRT indicated temperature to that of the blackbody [8,9]. Recently it was shown that the temperature displayed by an LPRT could drift by as much as 2 °C during the 10 min period immediately after the lightpipe is inserted into the blackbody [8]. This result implied that the temperature of an LPRT and other environmental factors might influence the LPRT indicated temperature. If this is the case, characterizing these environmental influences is important to minimize LPRT calibration and measurement uncertainties.

In this paper we present the results of experiments designed to study the effects of the environment of a lightpipe on the temperature indicated by the LPRT. The studies were made as the LPRT was gathering radiation from a constant-temperature blackbody source. The experiments performed demonstrated that the temperature of a lightpipe and the radiation surroundings could significantly affect the temperature displayed by an LPRT. They showed that the resulting measurement error is much higher when the temperature of the lightpipe environment is considerably higher than that of the LPRT target, implying that use of LPRTs in such an environment should be avoided if possible. The experiments indicated that measurement uncertainty due to environmental influence could be minimized by calibrating the LPRT in an environment similar to that in which it will be used. They showed that some lightpipes are less affected by their environment than others, suggesting that careful selection of lightpipes can also minimize the measurement uncertainty. A partial summary of the results of these experiments has been previously published [10].

2. LIGHTPIPES AND BLACKBODY SOURCE

The LPRTs studied were commercially made and consisted of three 2-mm diameter sapphire lightpipes connected to a 0.95-μm wavelength radiometer with 1-mm diameter optical fibers. They measured radiance temperature but not emissivity. Sapphire sheaths of 3.8-mm outer diameter, 3.3-mm inner diameter, and 9-cm length surrounded the lightpipes. Two LPRT systems from two different manufacturers were used in the experiments. Each LPRT system included four sets of lightpipes, yielding a total of eight lightpipes.

The blackbody source used was provided by the NIST Optical Temperature and Source Group and is the source used for the calibration of customer LPRTs [8]. It is a sodium heat-pipe blackbody source that has been described in detail previously [8]. In brief, the blackbody source is 2.5 cm in diameter, 48 cm in depth, and has a conical closure at the far end. Its emissivity has been calculated to be 0.99992. The temperature of the blackbody is measured with a Au/Pt thermocouple that has been calibrated with an uncertainty (k=1) of 0.005 °C.

Before conducting any experiments, the lightpipes were calibrated against the blackbody source at 750 °C, 800 °C, 850 °C, and 900 °C. The calibration was performed by controlling the blackbody temperature at 900 °C, inserting the lightpipe into the blackbody, and then setting the LPRT sensor factor so that the LPRT indicated the same temperature. At the other temperatures, the difference between the blackbody temperature and that on the LPRT indication was recorded to complete the calibration. During the procedure, each lightpipe was separately inserted 7 cm into the blackbody. The calibration was promptly made once the temperature reading stabilized, which was typically 2 s to 3 s.

3. FURNACE EXPERIMENT

The first experiment examined the influence of a hot radiative environment on the indicated LPRT temperature. As shown in Figure 1, a furnace surrounded the lateral surface of the lightpipe and heated it while the lightpipe was aimed at a constant radiance source, the blackbody. The centerpiece of the furnace was a heater composed of an alumina tube of inner diameter 4.8 mm, outer diameter 6.4 mm and length 7.0 cm, with a Pt/30Rh wire wrapped around the outside of the tube. A 4.3-cm thick layer of fiber insulation surrounded the heater. A Pt/Pd thermocouple coupled with an eight-digit multimeter measured the temperature of the outside of the wrapped heater wire halfway along its

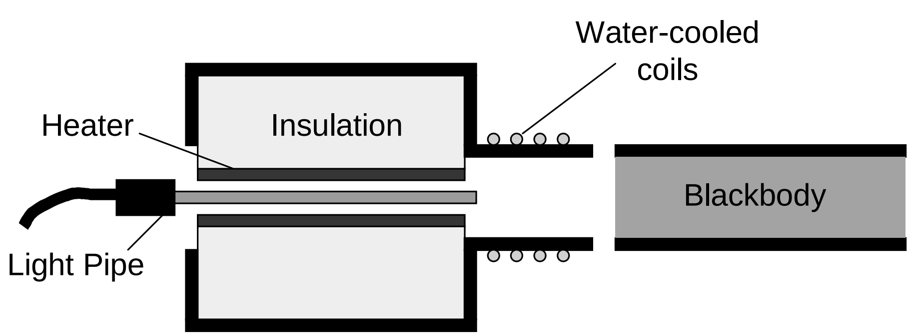

Figure 1. Schematic of furnace experiment.

length. The furnace was heated using a 250 W power supply. Since the blackbody aperture was 3 cm from the lightpipe tip and only filled part of the lightpipe field-of-view, the temperature indicated by the LPRT was typically 50 °C less than the blackbody temperature. A 2.2-cm diameter water-cooled tube surrounded the space between the lightpipe and the Na-HPBB aperture. This tube in turn was covered on the inside by a high-emissivity coating to minimize reflections of radiation originating from the furnace and detected by the LPRT. Before each experimental run, the initial indicated temperature T_o of the blackbody source by the LPRT was recorded. During the run, the furnace was turned on to a constant power and the temperature of the furnace increased with time from 21 °C up to approximately 950 °C after 30 min. The furnace temperature T_f and the LPRT indicated temperature T were recorded as a function of time. The temperature increase $T–T_o$ was then plotted as a function of T_f for four different values of T_o: 300 °C, 680 °C, 730 °C, and 780 °C. For the first value of T_o, the blackbody was at room temperature but the indicated temperature was the lowest readable temperature of the LPRT, 300 °C.

Figure 2 shows the results of this experiment with lightpipe #3 of LPRT #1. For all blackbody temperatures, the temperature indicated by the LPRT clearly increased when the furnace was heated, as shown in Figure 2a. When T_o was at 680 °C or above, the increase in T from T_o was as large as 60 °C when the furnace temperature was 950 °C. However, $T–T_o$ was always less than 4.5 °C when T_f was at or below the blackbody temperature. Also, the increase at a given furnace temperature was smaller as the blackbody temperature increased. This dependence on the blackbody temperature can be explained by converting the indicated temperature change to a radiance change using the relation

$$L_{\lambda,b}(\lambda,T) = c_1\lambda^{-5}e^{-c_2/\lambda T}, \tag{1}$$

where L is the radiance, λ is the radiation wavelength, T is the temperature, and c_1 and c_2 are the first and second radiation constants, respectively. The conversion is shown in Figure 2b, which demonstrates that the indicated temperature changes are traceable to identical indicated radiance changes. The results of Figure 2 show that extraneous radiation can reach the LPRT photodetector when the lightpipe is surrounded by a source of heat and/or radiation.

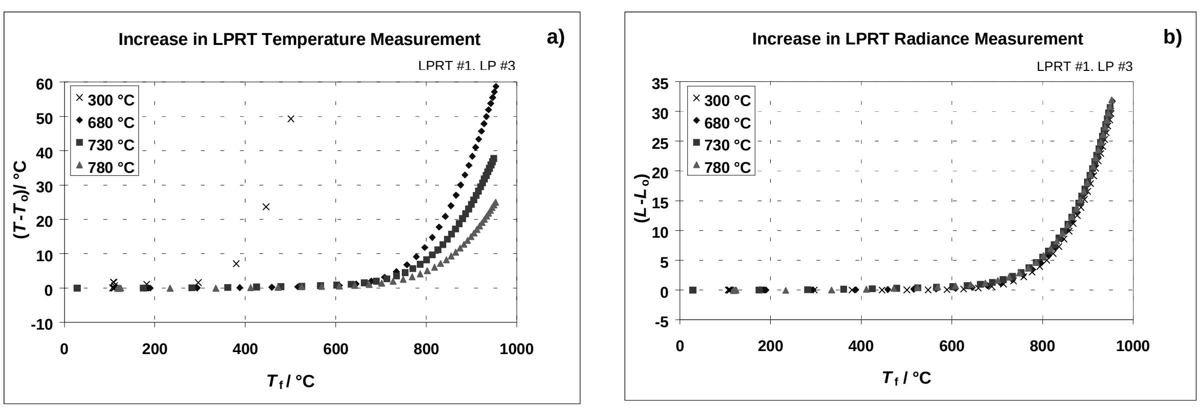

Figure 2. a) Increase in the indicated temperature T from the initial indicated temperature T_o as a function of furnace temperature T_f for lightpipe #3 of LPRT #1. The symbols represent different blackbody temperatures. b) Increase in LPRT indicated radiance L from the initial indicated radiance L_o as a function of T_f. The data is that from Figure 2a.

Figure 3a shows the results at T_o = 680 °C for the four lightpipes of LPRT #1. Above 700 °C, a significant difference exists between lightpipes in the values of $T–T_o$ for a given T_f. This demonstrates that the amount of extraneous radiation leaking into the LPRT varies considerably between individual lightpipes. In Figure 3b, the value of $T–T_o$ is plotted as a function of T_f for that time during the

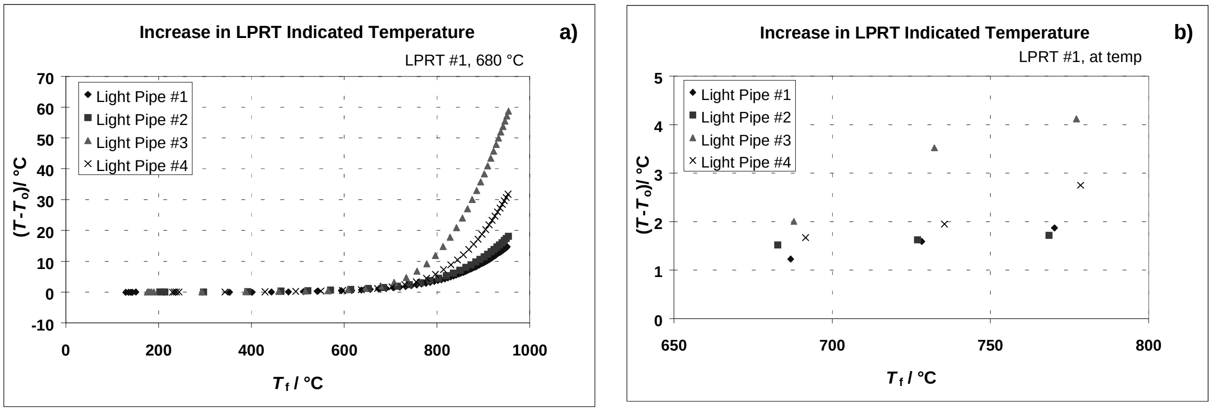

Figure 3. Increase in the indicated temperature T from the initial indicated temperature T_o as a function of furnace temperature T_f for the four lightpipes of LPRT #1. a) For T_o = 680 °C. b) At that time when the furnace temperature is equal to T_o for T_o = 680 °C, 730 °C and 780 °C.

experimental run when T_f was approximately equal to T_o for T_o = 680 °C, 730 °C and 780 °C. This simulates an operating environment where the temperature of the surroundings of the lightpipe is equal to that of the LPRT target (as the case when the lightpipe is inserted inside a blackbody cavity for calibration). The results for the four lightpipes of LPRT #1 are shown. The values of T–T_o range between 1 °C and 4.5 °C. Though considerably less than the values observed when T_f is much higher than T_o, they are still significant considering the uncertainties desired for temperature measurement and calibration with LPRTs.

4. WATER-COOLED SLEEVE EXPERIMENT

The second experiment, shown in Figure 4, examined the influence of the blackbody environment on the temperature indicated by an LPRT. For this experiment, a water-cooled sleeve was constructed out of a thin-wall, stainless steel tube, as shown. The sleeve had an inner diameter of 0.3 cm and an outer diameter of 1.3 cm. When used, the sleeve surrounded the lateral surface of the lightpipe as it was inside the blackbody source. The cold sleeve served both to keep the lightpipe temperature below 100 °C and to block radiation from entering its sides. For the experiment, the indicated temperature of the LPRT was monitored as a function of time t inside the blackbody with and without the cold sleeve. The two results were then compared with each other.

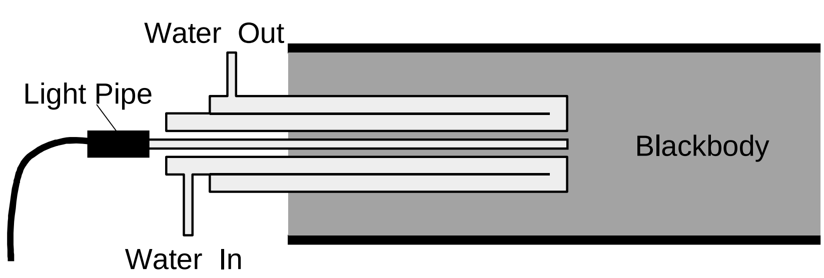

Figure 4. Schematic of Water-cooled sleeve experiment

Figure 5a shows the results of the cold sleeve experiment with lightpipe #3 of LPRT #1. When the cold sleeve was absent, the indicated temperature drifted higher by approximately 2 °C over 400 s before becoming steady. With the cold sleeve present, the temperature displayed by the LPRT did not

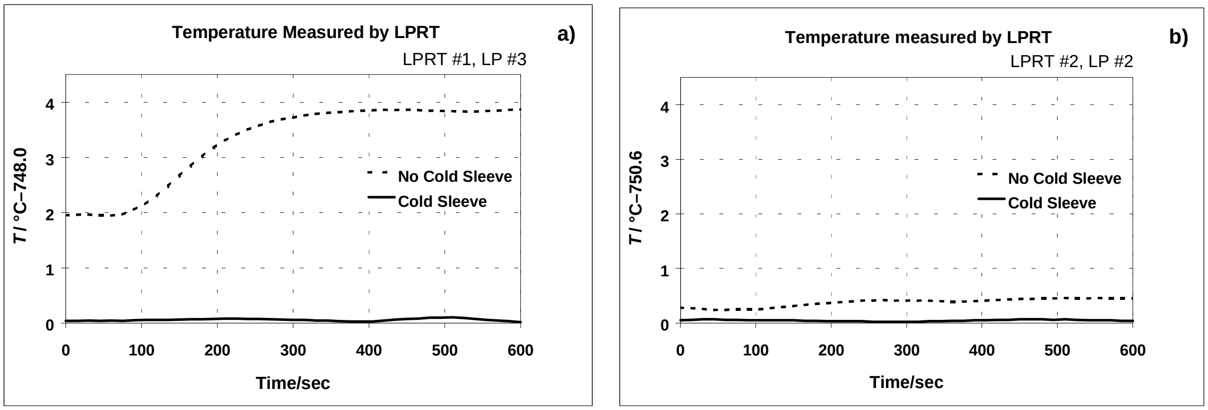

Figure 5. Temperature indicated by two LPRTs in the blackbody as a function of time. In a) lightpipe #3 of LPRT #1 is used and in b) lightpipe #2 of LPRT #2 is used.

drift. In addition, before the lightpipe was significantly heated, the temperature indicated by the unsleeved LPRT at $t = 0$ s was higher by $\Delta T(t = 0) = 2$ °C. Figure 5b shows the results with lightpipe #2 of LPRT #2. Once again the temperature indicated by the LPRT with the cold sleeve present did not drift. In this case, however, the temperature at $t = 0$ s measured without the cold sleeve was only about 0.2 °C and the temperature drifted up only by about 0.1 °C. For the other lightpipes, the results ranged between those found in a) and in b). Those lightpipes that showed a large $\Delta T(t = 0)$ also showed a large drift with time when the lightpipe was unsleeved. Some of the value of $\Delta T(t = 0) = 0.2$ °C in Figure 5b may be due to the thermal perturbation on the blackbody caused by insertion of the cold sleeve. Since the thermal perturbation on the blackbody was the same for all lightpipes, no more than 0.2 °C of the value of $\Delta T(t = 0) = 2.0$ °C shown in Figure 4a can be attributed to this perturbation. Also, we note that when the cold sleeve was inserted, the blackbody temperature as monitored by the thermocouple did not change and so it is unlikely that the radiation from the blackbody was disturbed. Aside from the thermal perturbation described above, the value of $\Delta T(t = 0)$ quantifies the blackbody calibration error due to light scatter from irradiation of the unsleeved lightpipe from the sides. The drift in indicated temperature of the unsleeved lightpipe over the first 400 s in the blackbody demonstrates that additional radiation was emitted from the lightpipe after it reached a sufficiently high temperature. A likely cause of this emission was the presence of impurities in the sapphire crystal of the lightpipe. For different lightpipes, the drift ranged from 0.2 °C to 2.0 °C, and those lightpipes with the smallest drift were the same ones where $\Delta T(t = 0)$ was smallest. This result shows that some lightpipes were less susceptible to extraneous radiation than others and suggests that careful selection of lightpipes can minimize calibration errors due to these effects. Calibrating the LPRT in an environment similar to that in which it will be used can also minimize these errors.

SUMMARY

We have performed experiments that demonstrate that extraneous radiation can be transmitted and emitted by LPRTs. This radiation can cause significant errors in the calibration and measurement of LPRTs if care is not taken to avoid this radiation and account for it. The furnace experiment showed that the errors in the indicated temperature are partly dependent on the target temperature because the errors are directly traceable to errors in the indicated radiance. The temperature-measurement errors are usually less than 4 °C but can be much higher if the environment surrounding the lightpipes is at a considerably higher temperature than the target of the temperature measurement. The cold-sleeve experiment demonstrated and quantified the influence of extraneous radiation when the LPRTs are calibrated using a blackbody. It was able to identify two different types of extraneous radiation: that due to external radiation leaking into the sides of the lightpipe and that due to self-emission when the lightpipe becomes sufficiently hot. Finally, the cold-sleeve experiment introduced a method for shielding the light-pipe from both types of extraneous radiation during calibration. Both experiments showed that some lightpipes transmitted/emitted more extraneous radiation than others, indicating that careful selection of lightpipes is important for minimizing measurement errors due to extraneous radiation.

This work has also inspired other experiments for characterizing extraneous radiation on LPRTs. Tsai *et. al.* have performed studies on lightpipes when laser light is directed into the lightpipe from one end [10,11]. They have used an integrating sphere to detect the radiation leaking out of the sides of lightpipes under this arrangement. They have also photographed the sides of lightpipes in this configuration, clearly showing the laser light escaping through the sides of the lightpipe. As a result of the work presented here and that of Tsai *et. al.*, NIST now plans to calibrate lightpipes in an environment similar to the user environment [10,11]. With those lightpipes for which the user environment is cold, cold sleeves will be used around lightpipes when calibrating them in a blackbody source.

ACKNOWLEDGEMENTS

The author is grateful to the NIST Optical Temperature and Source Group for allowing use of its sodium heat-pipe blackbody source for these experiments and to Frank Lovas and Ben Tsai for assistance in using it. The author also thanks David DeWitt and Kenneth Kreider for helpful input on this project.

REFERENCES

1. Dils R.R., *J. Appl. Phys.*, 1983, **54**, 1198-1201
2. Dils R.R., Geist J., Reilly M.L., *J. Appl. Phys.*, 1986, **59**, 1005-1012
3. Adams B.E., *Temperature: Its Measurement and Control in Science and Industry*, 1992, **6**, 739-743
4. DeWitt D.P., Sorrell F.Y., Elliott J.K. , In *Mat. Res. Soc. Symp. Proc*., Vol. 470 (Edited by T.J. Riley, J.C. Gelpey, F. Roozeboom, S. Saito), San Francisco, MRS, 1997, 3-15
5. Adams B.E., In proceedings of *TEMPMEKO '99* (Edited by J.F. Dubbeldam, M.J. de Groot), Delft, NMi, 1999, 3-10
6. Tsai B.K., DeWitt, D.P., Lovas F.J., Kreider K.G., Meyer C.W., Allen D.W., In proceedings of *TEMPMEKO '99* (Edited by J.F. Dubbeldam, M.J. de Groot), Delft, NMi, 1999, 726-731
7. Hebb J., Shajii, A., In proceedings of *7th Int. Conf. On Adv. Therm. Process of Semicond—RTP '99* (Edited by H. Kitayama, B. Lojek, G. Miner, A. Tillmann), Colorado Springs, RTP '99, 1999, 120-124
8. Lovas F.J., Tsai B.K., Gibson C.E., in *Mat. Res. Soc. Symp. Proc*., Vol. 525 (Edited by _zturk, Roozeboom, Timans, Pas), San Francisco, MRS, 1998, 127-133
9. Dils R.R., Yam M., Alex R., Hunter A., Adams B., In proceedings of *7th Int. Conf. On Adv. Therm. Process of Semicond—RTP '99* (Edited by H. Kitayama, B. Lojek, G. Miner, A. Tillmann), Colorado Springs, RTP '99, 1999, 148
10. Tsai B.K., Meyer C.W., Lovas, F.J., In proceedings of *8th Int. Conf. On Adv. Therm. Process of Semicond—RTP '2000* (Edited by D.P. DeWitt, J. Kowalski, B. Lojek, A. Tillmann), Gaithersburg, RTP '2000, 2000, 83-93
11. Tsai B.K., DeWitt, D.P., to be published in proceedings of *TEMPMEKO 2001*

Address of the Author:

Dr. Christopher Meyer, National Institute of Standards and Technology, 100 Bureau Drive, Stop 8363, Gaithersburg, MD 20899-8363, USA, E-mail: Christopher.meyer@nist.gov,
Internet: http://www.cstl.nist.gov/div836/836.05/home.htm