XVIII IMEKO WORLD CONGRESS
Metrology for a Sustainable Development
September, 17 – 22, 2006, Rio de Janeiro, Brazil

HYBRID TYPE SURFACE THERMOMETER

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Abstract: A hybrid-type surface thermometer combines the contact and non-contact methods, which allows us to overcome the shortcomings of both methods. The hybrid-type surface thermometer is a modified radiation thermometer. Temperature measurement using this thermometer is possible within a random error of ±0.5 K at temperatures of around 1000 K. This thermometer provides a useful means for calibration of in-situ temperature measurement in various processes, especially in the semiconductor industry. This paper introduces the basic idea of the hybrid-type surface thermometer, presents experimental results and discussions, and finally describes an application.

Keywords: radiation thermometry, thermal contact resistance, metal film, emissivity, semiconductor wafer.

1. INTRODUCTION

Temperature is one of the most basic and important physical quantities in a variety of fields. Thus, many methods for temperature measurement exist, and research and development on temperature measurement has actively been pursued [1-2].

Surface temperature measurement methods are broadly classified into two categories: contact methods, such as the use of a thermocouple [3-5], and non-contact methods, such as radiation thermometry [6]. The former have the advantage of stable measurement under appropriate thermal contact, but these are not applicable to moving objects and deteriorate due to changes in the circumference. On the other hand, the latter methods have the great advantage of being non-contact techniques and enable a rapid response, but, in the case of radiation thermometry, the variation in the emissivity of the object presents a serious problem. That is, if the emissivity of the object changes, radiation thermometry can no longer accurately measure the temperature of the object.

The hybrid-type surface thermometer described in this paper combines the advantages of contact and non-contact methods, offering a way of overcoming the weak points of both methods. It may be said that the hybrid-type surface thermometer is actually a modified radiation thermometer. We devised a hybrid-type surface temperature sensor and carried out experiments on a number of specimens. As a result, we confirmed that temperature measurement using the hybrid-type surface thermometer was possible within a random error of ±0.5 K in the temperature range from 900 to 1000 K. The present paper is a detailed account of the basic idea of the hybrid-type surface thermometer, its construction, and experimental results. An application is introduced, such as the simultaneous measurement of temperature and emissivity during processing.

2. PRINCIPLE

Figure 1 shows the concept of a hybrid-type surface thermometer, which is composed mainly of two components: i) a metal film that makes contact with the object and measures its temperature, and ii) a radiometer that is used to detect the radiance of the rear surface of the metal film. If the rear surface of the film is blackened so that its emissivity approaches 1.0, the true temperature of the metal film can be derived from the radiance signal detected by the radiometer. Under the thermally steady condition between the object and metal film, the true surface temperature of the object can be ascertained from the temperature reading of the rear surface of the metal film by the radiometer, irrespective of the emissivity change of the measured object.

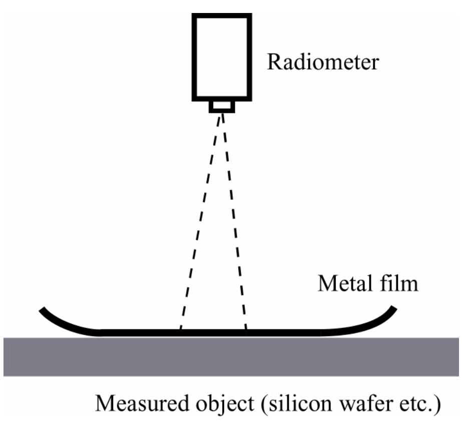


Fig. 1. Principle of the hybrid surface thermometer.

3. EXPERIMENTS

Figure 2 schematizes the hybrid-type surface thermometer system developed for experiments. Both sides of the metal film are supported by quartz plates, and its central portion can intermittently contact a specimen surface, made to move by a vertical controller. The metal film has a rectangular shape, 20-40 μm in thickness, 10 mm in width, and 27 mm in length, but the practical length of the metal film making contact with the specimen is 5 mm. The contact pressure of the metal film on the specimen is set to about 4×10^4 Pa. A fiber-type radiometer (Model IR-FBWS-SP, CHINO) sensitive at a wavelength of 0.9 μm (see left-hand side of Fig. 2) is used for calibration, that is, to detect the radiance of the specimen whose surface is coated with heat-resistant black paint. The emissisivity of the specimen reaches about 0.95. Thus, the temperature reading obtained by this radiometer after correcting for the emissivity corresponds to the true temperature of the specimen. The temperature reading of the hybrid-type surface thermometer is compared with the temperature reading of this radiometer. Temperature differences between the two reflect systematic errors due mostly to the thermal contact resistance between the specimen and metal film [7-8]. Besides systematic errors, fluctuations in the reading of the hybrid-type surface thermometer can also be linked to random errors of temperature caused by the hybrid-type surface thermometer.

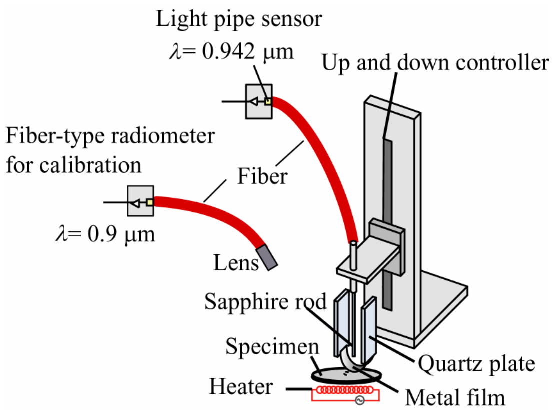


Fig. 2. Schematic of a hybrid-type thermometer system.

Figure 3 shows the metal film in a hybrid-type thermometer. The metal film and the tip of the sapphire rod are spaced closely, with a gap of 1 mm. Thus, the radiant flux originating from the rear surface of the metal film, from an area 4 mm in diameter, is incident on the sapphire rod, transmitted to the light pipe sensor through the rod and optical fiber, and detected as the radiance signal of the specimen. A commercially available optical light pipe sensor (Model OR1000F, ADVANCED ENERGY) having a sapphire rod is used as the radiometer for the hybrid-type surface thermometer, in which a silicon sensor sensitive at a wavelength of 0.942 μm is used [9]. Several materials, such as hastelloy, inconel, titanium and stainless steel, were tested in advance to find out if they would meet the requirements for use as a metal film in experiments at high temperature. Hastelloy and inconel were selected. Thus, hastelloy and inconel sheets of varying thickness were prepared and tested for further experiments.

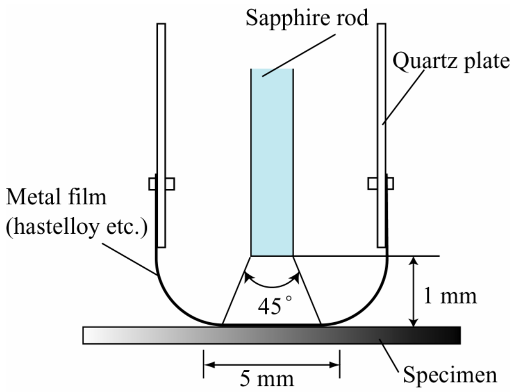


Fig. 3. Tip of a hybrid-tytpe thermometer.

Table 1 shows the thickness of the metal films. As specimens to be measured, stainless steels (SUS 304) 5.3 mm in thickness and 88 mm in diameter and n-type silicon wafers 0.5 mm in thickness and 76 mm in diameter are used as shown in Table 2. Both specimens have specularly reflecting surfaces which the metal film contacts. In order to compare the temperature measured by the hybrid-type surface thermometer with the temperature obtained by the fiber-type calibration radiometer, the specimens are painted in advance with the blackbody coatings. The temperature of the heater is controlled so that the surface temperature of the specimen changes between 900 and 1000 K.

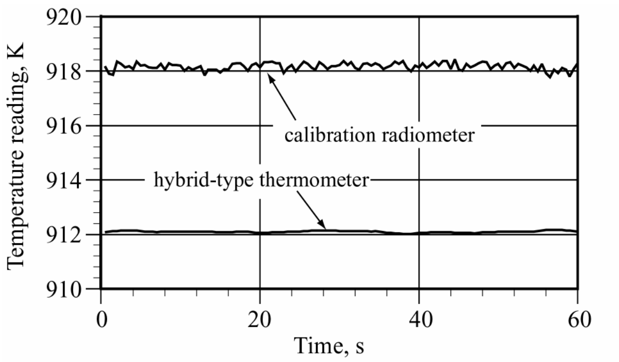
Table 1. Metal film thickness.

	Thickness (μm)	
Hastelloy	20	30
Inconel	25	40

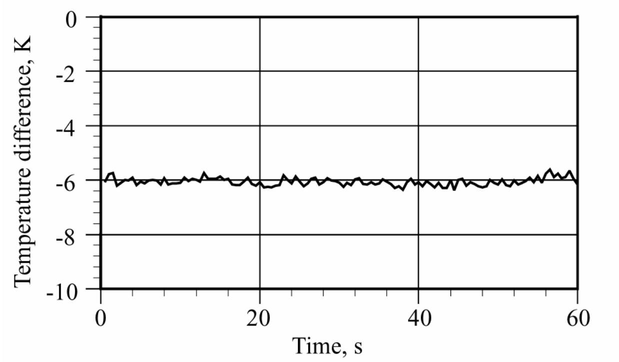
Table 2. Specimen dimensions.

Material	Size (mm)
Stainless steel (SUS304)	88 in diameter 5.3 in thickness
Silicon wafer (n-doped, 1 Ωcm)	76 in diameter 0.5 in thickness

Figures 4(a) and (b) show measurements by the fiber-type calibration radiometer and the hybrid-type surface thermometer for a stainless steel specimen using as metal film a 30-μm-thick hastelloy sheet at around 900 K, where (a) indicates the temperature readings of the fiber-type calibration radiometer and the hybrid-type surface thermometer, and (b) shows the differences between the two temperature readings. The average readings of the temperature differences represent the systematic temperature errors. The fluctuations of temperature readings are small because the stainless steel sheet is rather thick and the heat capacity of the specimen is quite large.



(a) temperature readings.



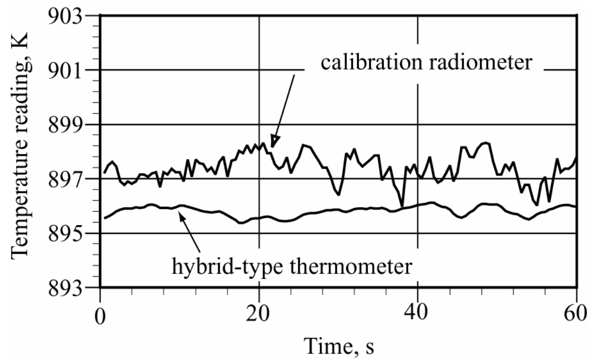
(b) temperature differences between the two temperature readings.

Fig. 4. Measurements obtained by the fiber-type calibration radiometer and the hybrid-type thermometer. (specimen: stainless steel).

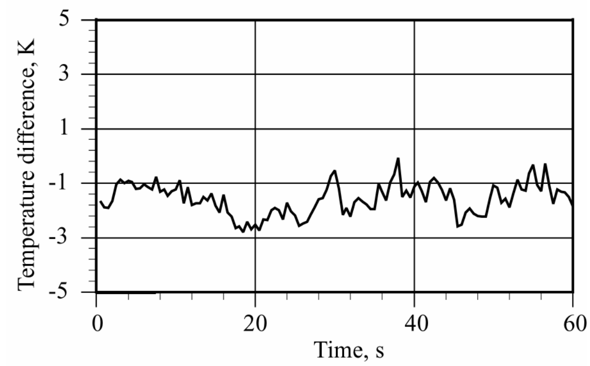
Similarly, Figures 5(a) and (b) show measurements by the fiber-type calibration radiometer and the hybrid-type surface thermometer for a silicon wafer specimen using as metal film a 25-µm-thick inconel sheet at around 900 K, where (a) shows the temperature readings of the fiber-type calibration radiometer and the hybrid-type surface thermometer, (b) the differences between the temperature readings. The average readings of the temperature differences are systematic temperature errors. The fluctuations in the temperature readings are rather large because the silicon wafer is thin and the heat capacity of the specimen is quite small. Thus, the readings of surface temperature are affected by fluctuations in air streaming.

We repeated these experiments for the combinations of metal films and specimens listed in Tables 1 and 2. Figures 6(a) and (b) compare the temperature differences between the fiber-type calibration radiometer and the hybrid-type surface thermometer for different metal films around 900 K for (a) stainless steel and (b) silicon wafer specimens. The temperature difference for each metal film corresponds to fluctuations of the measurement, namely, random errors.

Tables 3(a) and (b) show the quantitative evaluation of the measured temperature differences between the fiber-type radiometer and hybrid-type surface thermometer for, respectively, the stainless steel and silicon wafer specimens in Fig. 6. The average temperature difference represents systematic errors, and the fluctuations reflect random errors. The variance and standard deviation of random errors are also listed in Table 3. As shown in Fig. 6 and Table 3, the temperature differences between the calibration radiometer and the hybrid-type surface thermometer show a slight dependence on the metal film and its thickness. Hastelloy with a thickness of 30 µm as a contacting metal film is selected for further use in experiments.



(a) temperature readings.



(b) differences between the temperature readings.

Fig. 5. Measurements obtained by the fiber-type calibration radiometer and hybrid-type thermometer. (specimen: silicon wafer).

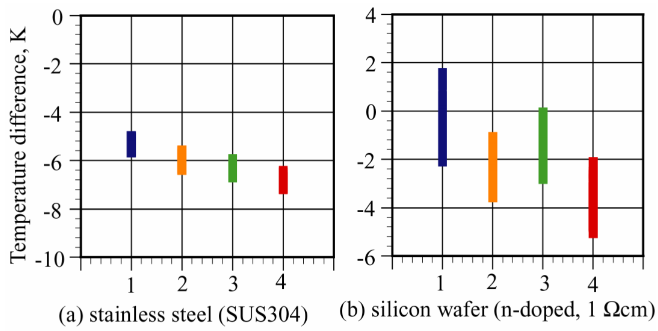


Fig. 6. Comparizon of temperature reading differences between the calibration radiometer and hybrid-type thermometer for different metal films and different thicknesses.

Figures 7(a) and (b) show the changes of temperature reading differences between the fiber-type calibration radiometer and the hybrid-type surface thermometer from 900 to 1000 K using the 30-µm-thick hastelloy film. With increasing temperature, the temperature differences, that is, systematic errors, increase for stainless steel, but remain constant in the case of the silicon wafer. The variance of the temperature difference, that is, the variance of random errors, however, is limited to 0.04 K for stainless steel, and 0.4 K for the silicon wafer.

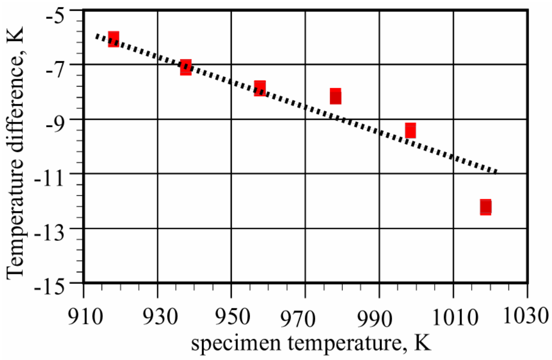
Table 3. Quantitative evaluation of the hybrid-type thermometer at around 900 K.

(a) Stainless steel (SUS304)

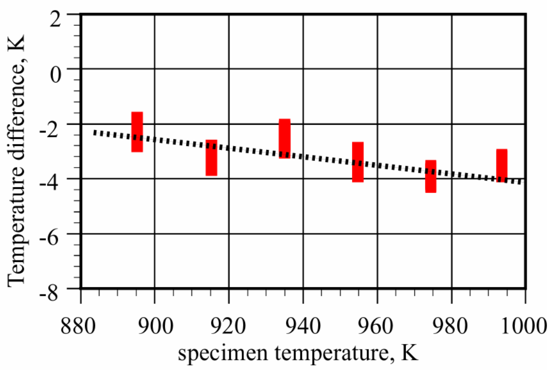
	Hastelloy 20 μm	Hastelloy 30 μm	Inconel 25 μm	Inconel 40 μm
Average K	- 5.51	- 6.07	- 6.30	- 6.94
Variance K	0.03	0.02	0.02	0.02
Standard deviation K	0.17	0.15	0.15	0.13

(b) Silicon wafer (n-doped, 1 Ωcm)

	Hastelloy 20 μm	Hastelloy 30 μm	Inconel 25 μm	Inconel 40 μm
Average K	- 0.66	- 2.37	- 1.58	- 3.97
Variance K	0.52	0.31	0.33	0.32
Standard deviation K	0.72	0.55	0.57	0.56



(a) stainless steel (SUS304)



(b) silicon wafer (n-doped, 1 Ωcm)

Fig. 7. Experimental relationship between the specimen temperature and temperature difference.

The results of our experiments can be summarized as follows:

(1) A hastelloy and inconel yield good results as the tip of the metal film for contact with specimens over the temperature range of 900-1000 K (Fig. 6).

(2) In case of a stainless steel specimen, systematic temperature errors are large, but the random temperature errors are small and their variance is very small (0.04 K, Fig. 4 and Table 3(a)).

(3) In case of a silicon wafer specimen, systematic temperature errors are small, but the random temperature errors are rather large and their variance is rather large as well (0.4 K, Fig. 5 and Table 3(b)).

(4) Systematic temperature errors increase with increasing temperature, but random temperature errors and their variance remain small and constant with increasing temperature in the case of stainless steel (Fig. 7(a)).

(5) Systematic temperature errors remain small with increasing temperature, and random temperature errors and their variance remain constant as well with increasing temperature in the case of a silicon wafer (Fig. 7(b)).

3. APPLICATION

The hybrid-type surface thermometer provides a useful means for in-situ measurement for cases where temperature measurement is difficult. An application is introduced here.

Figure 8 shows the measurements applied to silicon wafers. N-doped silicon wafers with a resistivity of 1 Ωcm and different oxide (SiO_2) film thicknesses d = 0 (bare), 150, 350, 550, 750 and 950 nm are prepared. Spectral, directional and polarized emissivities of these specimens at $\theta = 30°$ and $\lambda = 0.9$ μm are measured at about 930 K and displayed in Fig. 8 Both p- and s-polarized emissivities of these silicon wafers show cyclical changes with increasing oxide film thickness. The calibration system with the hybrid-type surface thermometer can easily measure the temperature and emissivity of silicon wafers whose temperature monitoring is otherwise very difficult.

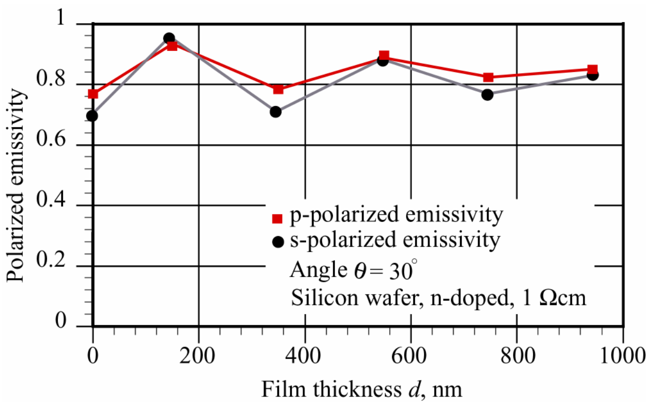


Fig. 8. Emissivity change of silicon wafers measured by the hybrid-type thermometer system as a function of oxide film thickness.

4. CONCLUSIONS

A hybrid-type thermometer, that is, a surface thermometer that combines contact and non-contact methods, has been developed. Though the response time of the hybrid-type surface thermometer is currently as long as 60 s, it enables the temperature measurement of a specimen, after compensating for systematic errors, with a random error of ±0.5 K in the temperature range from 900 to 1000 K. This surface thermometer is expected to provide a useful means for in-situ calibration in processes used, for example, in the silicon semiconductor industry [10], where temperature measurement of silicon wafers is very difficult. The proposed thermometer promises to be a powerful instrument for the simultaneous measurement of the temperature and emissivity of an object, provided the measurement system is composed of the hybrid-type thermometer and an additional radiometer.

ACKNOWLEDGMENTS

This research is funded by the Ministry of Education, Science, Sports and Culture under a Grand-in-Aid for Scientific Research (C) (project number 17560377) and also partially supported as “High-Tech Research Center” Project for Private Universities: matching fund from MEXT (Ministry of Education, Sports, Science and Technology), 2004-2008. This research is also funded by Toyo University under special research fund in 2005 fiscal year

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