Int J Thermophys (2008) 29:1166–1173
DOI 10.1007/s10765-008-0375-3

Rapid-Response Hybrid-Type Surface-Temperature Sensor

K. Hiraka · R. Shinagawa · A. Gogami · T. Iuchi

Abstract A hybrid-type surface-temperature sensor that combines the advantages of contact and non-contact sensing methods has been developed and that offers a way to overcome the weak points of both methods. The hybrid-type surface-temperature sensor is composed of two main components: a metal film that makes contact with the object and an optical sensor that is used to detect the radiance of the rear surface of the metal film. Temperature measurement using this thermometer is possible with an uncertainty of 0.5 K after compensating for systematic errors in the temperature range from 900 to 1,000 K. The response time of our previous hybrid-type sensor is, however, as long as several tens of seconds because the measurement must be carried out under thermally steady-state conditions. In order to overcome this problem, a newly devised rapid-response hybrid-type surface-temperature sensor was developed and that can measure the temperature of an object within 1 s by utilizing its transient heat transfer response. Currently, the temperature of a silicon wafer can be measured with an uncertainty of 1.0 K in the temperature range from 900 to 1,000 K. This sensor is expected to provide a useful means to calibrate in situ temperature measurements in various processes, especially in the semiconductor industry. This article introduces the basic concept and presents experimental results and discussions.

Keywords Calibration · Emissivity · High temperatures · Hybrid method · Response time

---

K. Hiraka · R. Shinagawa · A. Gogami
Department of Mechanical Engineering, Toyo University, 2100 Kujirai, Kawagoe, Saitama 350-8585, Japan

T. Iuchi (✉)
Sensor Photonics Research Center, Toyo University, 2100 Kujirai, Kawagoe, Saitama 350-8585, Japan
e-mail: iuchi@eng.toyo.ac.jp

1 Introduction

Surface temperature measurement methods are broadly classified into two categories: contact methods, such as a thermocouple [1–3], and non-contact methods, such as radiation thermometry [4,5]. Contact methods have the advantage of stable measurement under appropriate thermal contact, but they cannot be applied to moving objects and can deteriorate with time. Non-contact methods have the great advantage of rapid response but, in the case of radiation thermometry, the variation in the emissivity of the target presents a serious problem; if the emissivity of the object changes, radiation thermometry can no longer accurately measure the temperature of the object.

The hybrid-type surface-temperature sensor which the authors have developed combines the advantages of contact and non-contact methods and offers a way to overcome the weaknesses of both methods [6]. This sensor is actually a modified radiation thermometer that can be used for an emissivity-free measurement because the emissivity of the object does not affect the measurement of this sensor. The response time of this sensor, however, is several tens of seconds because a thermal steady state is required, and this does not meet the requirements for an in situ process measurement. Therefore, a newly devised hybrid-type surface-temperature sensor was developed, which is capable of rapid temperature measurements (within 1 s) by utilizing transient heat transfer in the temperature range between 900 and 1,000 K. This article introduces the basic concept of the hybrid-type surface thermometer and presents experimental results and discussion.

2 Measurement Principle

Figure 1 shows the overall concept of the proposed hybrid-type surface thermometer, which is comprised of two primary components: (i) a metal film that makes contact

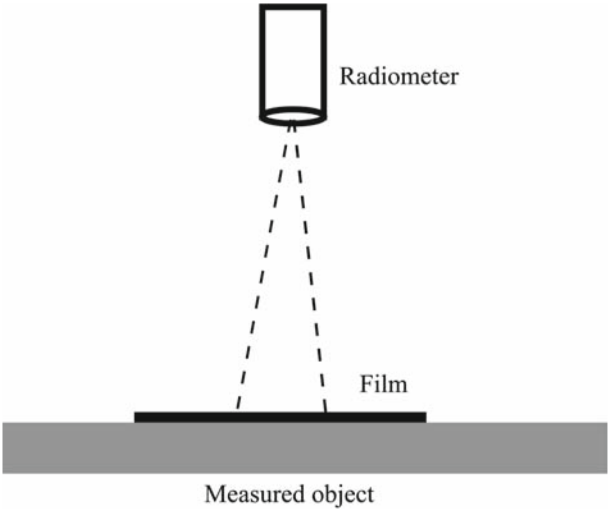

Fig. 1 Principle of the hybrid-type surface temperature sensor

with the object and (ii) an optical sensor that is used to detect the radiance of the rear surface of the metal film. If the emissivity of the rear surface of the film is known in advance, the true temperature of the metal film can be derived from the radiance signal detected by the optical sensor after correcting for the known emissivity of the rear surface of the film. Under a thermally steady condition between the object and the metal film, the true surface temperature of the object can be ascertained from the temperature reading of the rear surface of the metal film, in spite of a possible emissivity change of the measured object.

A feasibility study for a rapid-response hybrid-type surface-temperature sensor was carried out using transient heat-transfer phenomena instead of thermally steady-state conditions. The lumped-capacitance method is introduced, the essence of which is the assumption that the temperature of the metal film is spatially uniform at any instant during the transient process. This assumption implies that temperature gradients within the film are negligible [7]. The value of the Biot number, *Bi*, is the criterion for this condition. If $Bi = hL/k < 0.1$ is satisfied, where k ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$) is the thermal conductivity, h ($\mathrm{W \cdot m^{-2} \cdot K^{-1}}$) is the convective heat transfer coefficient, and $L \equiv V/A$ (m) is the ratio of the film volume-to-surface area, then the error associated with the lumped-capacitance method will be small.

When the temperature gradients within the film are neglected, the transient temperature response is determined by formulating an overall energy balance for the film exposed to a convective boundary condition in air, as shown in the following equation:

$$\rho V c_p \frac{\mathrm{d}T}{\mathrm{d}t} = hA(T_\mathrm{f} - T) \tag{1}$$

Here, ρ is the density of the film ($\mathrm{kg \cdot m^{-3}}$), c_p is the specific heat at a constant pressure ($\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$), t is the time (s), T is the temporal temperature (K) of the film, and T_f is the film's final temperature (K). A general solution of Eq. 1 is obtained as

$$T - T_\mathrm{f} = C \exp(-\frac{hA}{\rho V c_p} t) \tag{2}$$

where C is constant.

If the initial temperature of the film sheet is $T = T_0$ at time $t = 0$, C is calculated as $C = T_0 - T_f$. Thus, Eq. 2 can be expressed as

$$T - T_\mathrm{f} = (T_0 - T_\mathrm{f}) \exp(-\frac{hA}{\rho V c_p} t) \tag{3}$$

The transient temperature response of the film T can be obtained from Eq. 3 as

$$\frac{T - T_0}{T_\mathrm{f} - T_0} = 1 - \exp(-\frac{hA}{\rho V c_p} t) = 1 - \exp(-\frac{t}{\tau}) \tag{4}$$

The quantity $\tau = \rho V c_p/(hA)$ defines the dynamic response of the system to an input and is known as a thermal time constant. The film's final temperature T_f can be

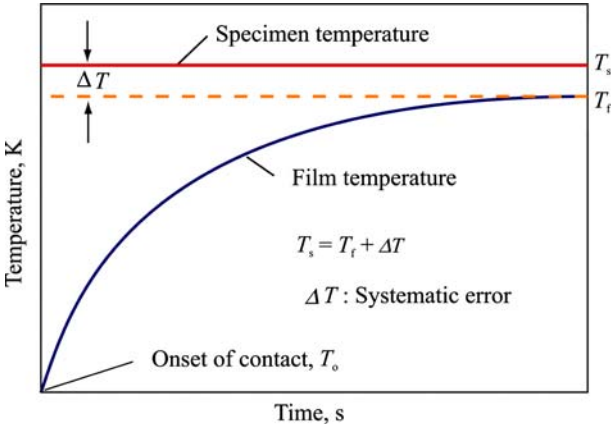

Fig. 2 Relationship between a temperature, $T_{\rm s}$, of the specimen and a final temperature, $T_{\rm f}$, of the film

estimated from the transient response of Eq. 4 using the temperature T of the metal film only subseconds after the contact onset.

Figure 2 shows the relationship between the transient temperature response of the film and the specimen's temperature, $T_{\rm s}$. After the film contacts the specimen, the film's temperature rapidly approaches the final temperature $T_{\rm f}$ in accordance with Eq. 4. There will be a temperature difference $\Delta T (= T_{\rm s} - T_{\rm f})$ between $T_{\rm s}$ and $T_{\rm f}$ because of the thermal contact resistance between the surfaces of the metal film and the specimen. Under the constant contact pressure of the metal film on the specimen, ΔT is kept constant. Therefore, ΔT is treated as the known systematic error. The true temperature $T_{\rm s}$ of the specimen can be obtained by adding the systematic error ΔT to the measured final temperature $T_{\rm f}$ as

$$T_s = T_{\rm f} + \Delta T \tag{5}$$

3 Experiments

Figure 3 shows a schematic of the hybrid-type surface-temperature sensor, which contains the metal film and the sapphire rod. Both ends of the metal film are supported by quartz plates. The film can intermittently contact a specimen surface through the use of a stepper motor. The contact pressure of the metal film on the specimen is set to 40–80 kPa. The metal film and the tip of the sapphire rod are spaced closely, with a gap of 1 mm. The radiant flux originating from an area 2.2 mm in diameter on the rear surface of the metal film is incident on the sapphire rod, and is then transmitted to the optical sensor through the rod and an optical fiber. This flux is finally detected as the radiance signal of the metal film. A commercially available optical light-pipe sensor (Model OR1000F, Advanced Energy) is used as the radiometer for the hybrid-type surface-temperature sensor. The radiometer contains a silicon sensor that is sensitive at a wavelength of 0.942μm. Hastelloy, a highly heat- and corrosion-resistant superalloy, composed of nickel and several other metals, is exclusively employed as the

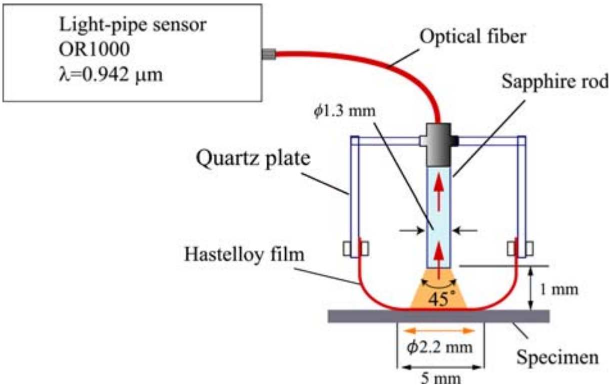

Fig. 3 Schematic of the hybrid-type surface-temperature sensor

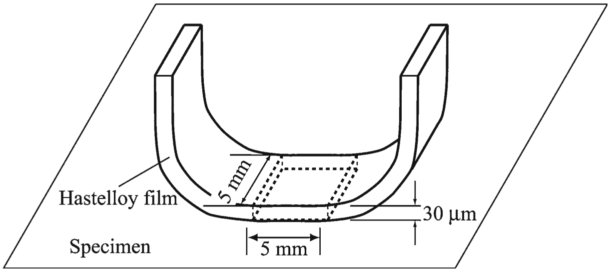

Fig. 4 Size of the contact portion of the hybrid-type surface-temperature sensor

film sheet. N-type (100) silicon wafers measuring 0.5 mm in thickness and 76.2 mm in diameter are used as the measurement specimens. The temperature of the heater is controlled so that the surface temperature of the specimen varies between 900 and 1,000 K, which is within the temperature range of the radiometer.

As shown in Fig. 4, the metal film (material: Hastelloy) making contact with the object has a rectangular shape and is 30μm thick, 5 mm wide, and the practical length of the metal film making contact with the specimen is 5 mm. Therefore, the sensor's volume, V, that contacts the specimen, is $V = 5 \times 10^{-3}$ m x 5×10^{-3} m x 30×10^{-6} m$=7.5\times10^{-10}$ m^3. The sensor's surface area, A, that contacts the specimen, is $A = 5 \times 10^{-3}$ m $\times$ 5×10^{-3} m$=2.5 \times 10^{-5}$ m^2. The Biot number, Bi, of the metal film sheet used in the experiments is calculated to be

$$B_i = \frac{hL}{k} = \frac{h\frac{V}{A}}{k} = \frac{100 \times \frac{7.5\times10^{-10}}{2.5\times10^{-5}}}{9.8} \approx 3 \times 10^{-4} << 0.1 \tag{6}$$

where $h = 100\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$ in air, $k = 9.8\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$ for Hastelloy, and $L = 30 \times 10^{-6}$ m (thickness).

The value of Bi is much smaller than 0.1. Therefore, the temperature of the Hastelloy film is considered spatially uniform. The thermal time constant, τ, is roughly estimated

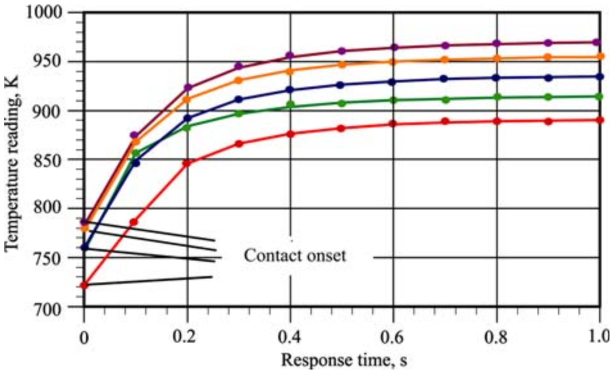

Fig. 5 Dynamic response of the hybrid-type surface-temperature sensor

to be $\tau = 1.1$ s using typical quantities: $\rho = 8.89 \times 10^3\ \mathrm{kg \cdot m^{-3}}$, $c_p = 4.27 \times 10^2$ $\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$ for Hastelloy, and $V/A = 30 \times 10^{-6}$ m.

Prior to the experiments, heat-resistant pseudo-blackbody coatings (Model CRC-1500, Nippan Laboratory) are painted on the specimens and the rear surface of the Hastelloy film of the hybrid-type surface-temperature sensor. The emissivity of the coatings is 0.95 according to the manufacturer's specification. The radiance of the specimen is monitored using a fiber-type radiometer (Model IR-FBWS-SP, Chino) and converted into a temperature reading after correcting for the coating emissivity of 0.95. Then, the Hastelloy film of the hybrid-type surface-temperature sensor makes contact with the specimen surface at a constant pressure of 40 kPa, and finally the radiance of the rear surface of the Hastelloy film is detected by the light-pipe sensor and converted into a temperature reading. The experiments were repeated in the 900–1,000 K temperature range.

Figure 5 shows the experimental results of the dynamic responses of the hybrid-type temperature sensor within 1 s of contacting the silicon wafers, depending on the initial temperature T_0. The measurements were carried out using 0.1 s steps.

Figure 6 shows the experimental results of the normalized temperature response $(T - T_0)/(T_\mathrm{f} - T_0)$ in accordance with Eq. 4. All of the normalized temperatures coincided within 1.0 s independent of the temperature range. The uncertainty of the measurement of the final temperature T_f was 0.5 K in the temperature range from 900 to 1,000 K. The uncertainty of the systematic temperature error ΔT in Eq. 5 was also 0.5 K in the temperature range between 900 and 1,000 K. Thus, the uncertainty of the true temperature T_s of the specimen was estimated to be 1 K.

4 Discussion

The dynamic temperature response of the film and the electronic output response of the sensor overlap within 0.2 s of the initial contact, which may cause a temperature error within the first 0.2 s, as shown in Fig. 6. In order to avoid the overlap, a highly responsive electronic sensor output in under 0.1 s is required.

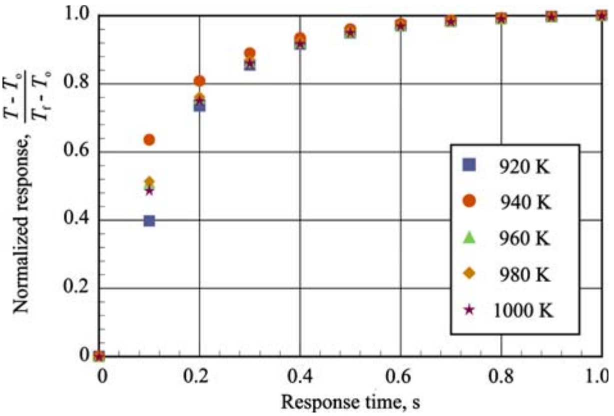

Fig. 6 Normalized temperature response of the hybrid-type surface-temperature sensor

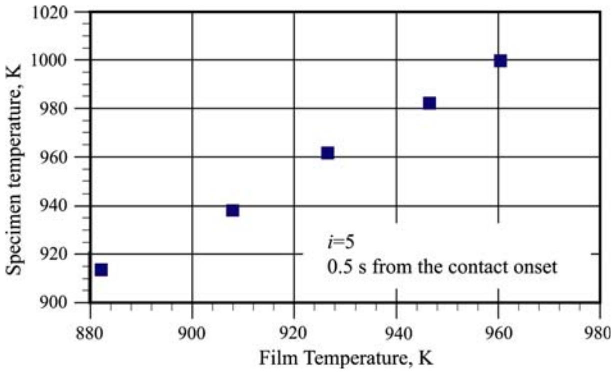

Fig. 7 Experimental relationship between the film temperature, T_i, at 0.5 s from the contact onset and the specimen temperature, T_s

Rigorously speaking, the transient temperature response in the high-temperature range should be formulated using Eq. 7 instead of Eq. 1 because the net heat transfer heavily depends on radiative heat transfer at high temperatures [6];

$$\rho V c_p \frac{\mathrm{d}T}{\mathrm{d}t} = hA(T_\mathrm{f} - T) - \varepsilon A\sigma(T^4 - T_\mathrm{sur}^4) \tag{7}$$

Here, ε is the emissivity of the specimen, σ is the Stefan-Boltzmann constant ($\sigma = 5.67 \times 10^{-8}\ \mathrm{W \cdot m^{-2} \cdot K^{-4}}$) and T_sur is the temperature (K) of the surroundings. The expression for estimating the temperature T_f of the film from the transient response described in Eq. 4 is difficult in the case of Eq. 7. Therefore, the transient temperature response should be experimentally determined.

Figure 7 shows the experimental relationship between the film temperature T_i and the specimen temperature T_s, where T_i denotes the transiently measured temperature of the film at the time of $i = 5$-steps from the initial contact, which corresponds to 0.5 s from the contact onset. A good linear relationship is found between T_i and T_s.

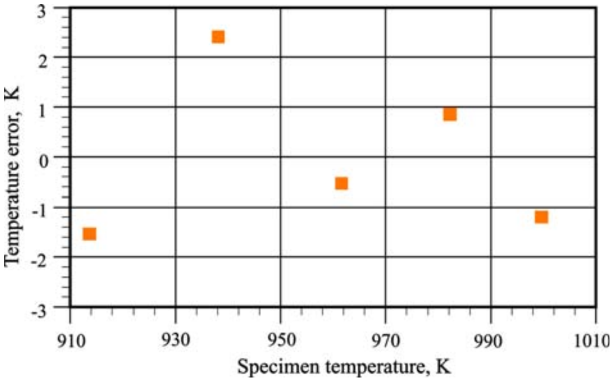

Fig. 8 Estimation error of the specimen temperature from the film temperature at 0.5 s

Using these relationships the error of the specimen temperature T_s is estimated to be no more than ±2 K, as shown in Fig. 8. The temperature estimated by this method seems to be adequate, but the method is too empirical to generalize over a wide temperature range.

5 Conclusions

A rapid-response hybrid-type surface-temperature sensor that has a 1 s response time was developed. A temperature measurement with this sensor is possible within ±1 K in the temperature range between 900 and 1,000 K. This sensor has potential for in situ calibrations of temperature measurements. If the metal film is replaced with a silicon film that is contaminant-free, the sensor will be especially useful in silicon semiconductor manufacturing processes.

Acknowledgments This work was funded by the Ministry of Education, Science, Sports, and Culture under a Grand-in-Aid for Scientific Research (C) (Project Number 17560377, 2005–2006) and also supported as a "High-Tech Research Center" Project for Private Universities: matching fund from MEXT (Ministry of Education, Sports, Science, and Technology), 2004-2008.

References

1. L. Michalski, K. Eckersdorf, J. MaGhee, *Temperature Measurement* (Wiley, New York, 1991), pp. 317–331
2. C.E. Moeller, in *Temperature: Its Measurement and Control in Science and Industry*, vol. 3, ed. by C. H. Herzfeld (AIP, New York, 1962), pp. 617–623
3. M. Jakob, *Heat Transfer*, vol. II (Wiley, New York, 1969), pp. 147–159
4. D.P. DeWitt, G.D. Nutter (eds.), *Theory and Practice of Radiation Thermometry* (Wiley, New York, 1988)
5. T. Iuchi, T. Furukawa, Rev. Sci. Instrum. **75**, 5326 (2004)
6. T. Iuchi, K. Hiraka, Rev. Sci. Instrum. **77**, 114902 (2006)
7. F. P. Incropera, D.P. DeWitt, *Fundamentals of Heat and Mass Transfer* (Wiley, New York, 2002), pp. 240–254