Non-Contact Temperature Measurements Using Thermocouple Placed in Hole in High-Temperature Subjects

Shigeki Hirasawa[*1], Hiroyuki Ageishi[2], Tsuyoshi Kawanami[3], Katsuaki Shirai[4]

[1-4]Department of Mechanical Engineering, Kobe University, 1-1 Rokkodai, Nada, Kobe, Hyogo, 657-8501, Japan

[*1]hirasawa@kobe-u.ac.jp

***Abstract*-New devices using non-contact temperature measurements for high-temperature subjects are needed for manufacturing processes. We analytically and experimentally studied the measurement error of a non-contact temperature measurement method using a thermocouple placed in a hole in a subject. Radiation heat transfer and thermal conduction for the thermocouple placed in the hole were calculated. We found that the measurement error of a non-contact temperature measurement method using a thermocouple placed in a hole of a 1000 ℃ subject was much lower than the measuring error of simple method using a thermocouple placed near a subject. The measuring error was less than 1 ℃ when the thermocouple in the hole was longer than 22 mm, or the diameter of the thermocouple was less than 0.15 mm. Steady temperature was measured by an experimental apparatus similar to the calculation model. Experimental results agreed with calculations.**

Keywords- Non-contact Temperature Measurement; Accuracy; Manufacturing Process; Heat Transfer

I. INTRODUCTION

In high-temperature processes for VLSI (Very Large Scale Integration) fabrication such as the oxidation and diffusion of implanted impurities, and uniform heating throughout silicon wafers becomes important as the diameter of wafers increases. In the above processes, hot wall diffusion furnaces are used, and no practical thermometry technique for silicon wafers exists. Bare thermocouples, the most popular thermometers, are not used because the heavy metals that comprise the thermocouples may contaminate the silicon wafers. Instead of using bare thermocouples, a thermocouple contained in a small quartz tube is inserted into a diffusion furnace to measure its internal temperature [1]. However, monitoring temperature inside a diffusion furnace by using the thermocouple contained in a small quartz tube is inaccurate due to the temperature difference between the wafers and the furnace. Similar problems exist in many manufacturing processes. Although it is important to know the actual temperature of products in the manufacturing process, to prevent contamination and inferior quality, manufactured products cannot come into contact with thermal sensors.

The most common method of non-contact temperature measurement uses a radiation pyrometer, which exploits the infrared radiation emitted from the surface of a measured subject [2, 3]. However, this radiation is not uniquely dependent upon temperature because the energy flux and spectral distribution are also functions of the spectral emissivity of the surface. Noise radiation emitted from surrounding objects such as heaters also results in large measuring errors. Moreover, it is difficult to measure the temperature at internal or inaccessible positions where radiation cannot be detected by the pyrometer sensor. To address these problems, new devices using direct non-contact measurement techniques are needed for high-temperature objects.

Various reports of non-contact temperature measuring techniques have been reported. Medvedev et al. [4] reviewed instruments for non-contact temperature measurements. Fothergill [5] reported a method of non-contact temperature measurement using forced air convection. Toyoda et al. [6] reported a method of non-contact temperature measurement of high-temperature silicon wafers based on the combined use of transmittance and radiance. Periyannan et al. [7] reported a method of temperature measurement using an ultrasonic waveguide. Non-contact surface thermocouples in reflectors of 25 mm in diameter were developed with an accuracy of ±5°C at 200°C [8]. These previous non-contact temperature measuring devices were not easy to use and demonstrated insufficient accuracy for high-temperature subjects in a furnace, requiring the development of a new simple and accurate non-contact method of temperature measurement.

In this work, we analytically and experimentally studied the measuring error of a method of non-contact temperature measurement using a thermocouple placed in a hole in a measuring subject.

II. ANALYTICAL METHOD

Fig. 1 depicts a model of a simple non-contact temperature measurement system using a thermocouple placed near a measured subject. A K-type thermocouple of 0.2 mm in diameter was wound around a quartz rod 5 mm in diameter; the temperature was measured at the end surface of the rod. The K-type thermocouple can be used to measure temperature up to 1000°C. The end surface of the rod was placed near the surface of the measuring subject (at a distance of less than 1 mm). The outside of the rod was thermally insulated to a thickness of 10 mm, except for the region located 10 mm from the end. The temperature of the measured subject was 1000°C, the temperature of the surrounding space was 25°C, and the space was under vacuum conditions. The radiation heat transfer between surfaces and the thermal conduction in the quartz rod were calculated. Emissivity of the measured subject and the thermocouple was assumed to be ε = 0.9 [2]. The thermal conductivities of the quartz, thermocouple and rock wool thermal insulator were λ = 3 W/mK, 73 W/mK and 0.08 W/mK, respectively [9].

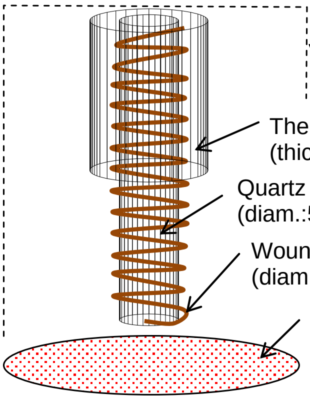

Fig. 1 Model of rod wound thermocouple

Fig. 2 shows a model of a revised non-contact temperature measurement system using a thermocouple placed in a hole in a measured subject. The hole was 3 mm in diameter and 20 mm in depth. The K-type thermocouple of diameter 0.2 mm was inserted into the hole without touching the subject, and the temperature was measured at the end point of the thermocouple. A pair of thermocouple wires is depicted as a rod in Fig. 2, with identical cross-sections. Radiation heat transfer between surfaces and the thermal conduction in the thermocouple were calculated. Creating a hole in the measuring subject would have contaminated it, but such a hole can be simulated with a small space in the measuring subject, such as the space between silicon wafers in a row in a diffusion furnace.

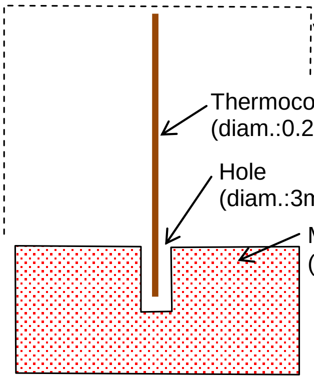

Fig. 2 Model of thermocouple in hole

The two-dimensional steady temperature distribution in the rod was calculated by the following equation [9]:

$$\lambda\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{\partial^2 T}{\partial z^2}\right\}+q_v=0 \tag{1}$$

where T is the temperature, r and z are coordinates, λ is thermal conductivity, and q_v is the radiation heat transfer rate per unit volume. The radiation heat transfer rate per unit area q between two close surfaces with temperatures T_1 and T_2 and emissivity ε_1 and ε_2 was calculated by the following equation [9]:

$$q=\frac{\sigma\left\{(T_1)^4-(T_2)^4\right\}}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1} \tag{2}$$

where σ is the Stefan-Boltzmann constant. Equations (1) and (2) were numerically calculated using the implicit finite difference approximation using an own calculation code. Mesh size was determined to be 1 mm by considering the temperature distribution within the object.

III. CALCULATION RESULTS

The calculation results of temperature distribution in the rod for a simple method of non-contact temperature measurement using a thermocouple placed near a 1000°C subject (Fig. 1) is shown by the black line in Fig. 3. The line curve was obtained from discrete calculation results by using the curve fitting technique. The measured temperature was 986°C, and the measuring error of the thermocouple was 14°C; this is inaccurate for practical use.

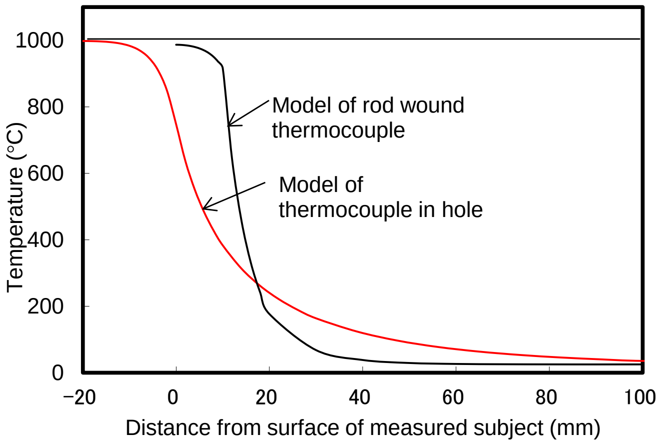

Fig. 3 Temperature distribution

The calculated temperature distribution in the thermocouple using a revised non-contact temperature measurement method using a thermocouple placed in a hole (Fig. 2) is shown by the red line in Fig. 3. The measured temperature was 998°C, and the measuring error of the thermocouple was 2°C. The measuring accuracy was thus improved, and is acceptable for practical use.

We calculated the effects of parameters on the measuring error of the revised non-contact temperature measurement method using a thermocouple placed in a hole. Fig. 4 shows the effect of the depth of the hole. The depth of the hole had a large effect, with a measuring error less than 1°C when with a hole depth greater than 22 mm. Fig. 5 shows the effect of the diameter of the thermocouple. The diameter also had a large effect, with a measuring error of less than 1°C with a hole diameter of less than 0.15 mm. Fig. 6 shows the effect of the temperature of the measured subject under vacuum conditions and under atmospheric conditions (with air in the space). The diameter of thermocouple was 0.2 mm, and the depth of the hole was 20 mm. The measuring error decreased for the high-temperature subject under atmospheric conditions because the heat transfer rate increased by thermal conduction of air through the hole. Fig. 7 shows the effects of surface emissivity of the hole and the thermocouple. The measuring error decreased with large emissivity due to the increase of the radiation heat transfer rate. We found that the measuring error of the proposed method of non-contact temperature measurement using a thermocouple placed in a hole at 1000°C was less than 1°C when the thermocouple in the hole was longer than 22 mm, or when the diameter of the thermocouple was less than 0.15 mm.

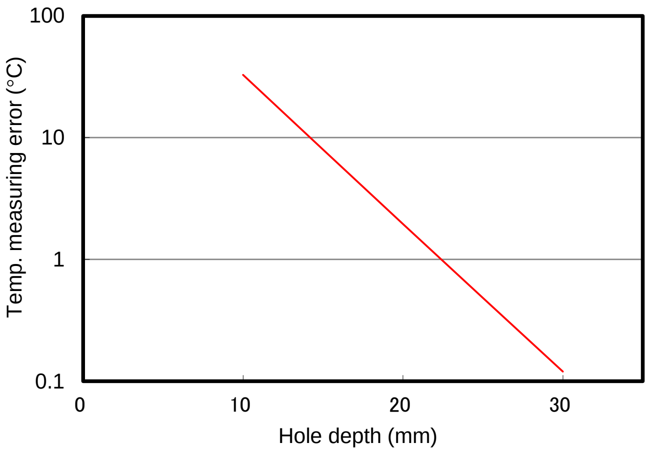

Fig. 4 Effect of hole depth on measuring error

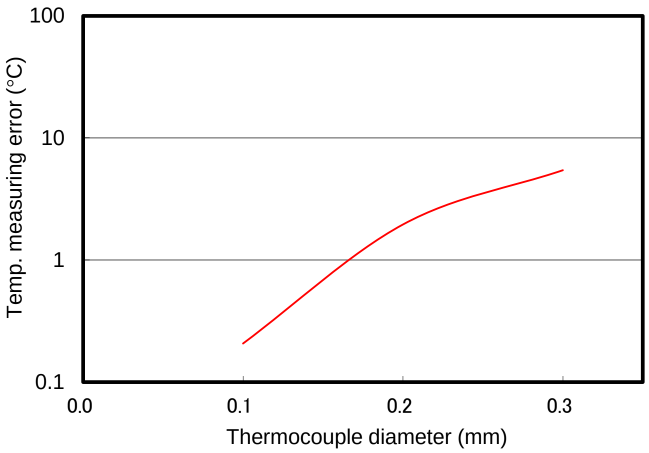

Fig. 5 Effect of thermocouple diameter on measuring error

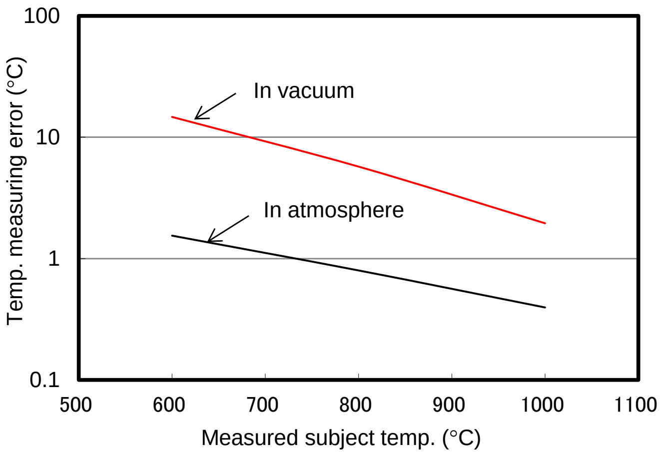

Fig. 6 Effect of measured subject temperature under vacuum and atmospheric conditions

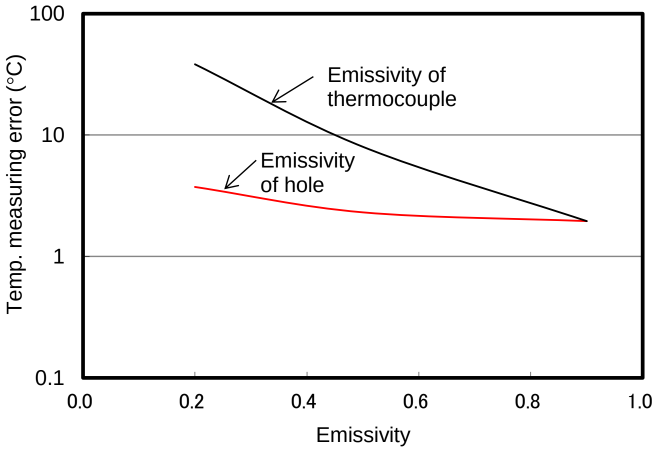

Fig. 7 Effect of hole and thermocouple emissivity on measuring error

The length of the thermocouple in the hole had a significant effect as shown in Fig. 4. So we calculated the measurements of thermocouple with a bent wire and a wound wire, as shown in Figs. 8 and 9. Both thermocouples were 30 mm in length and 0.2 mm in diameter, placed in a hole of 10 mm in deep and 3 mm in diameter. Calculations revealed measuring errors of 20°C for the bent wire (Fig. 8) and 1°C for the wound wire (Fig. 9). The measuring error did not decrease for the bent wire due to the radiation heat transfer among bent wires in the hole. However, the measuring error decreased for the wound wire.

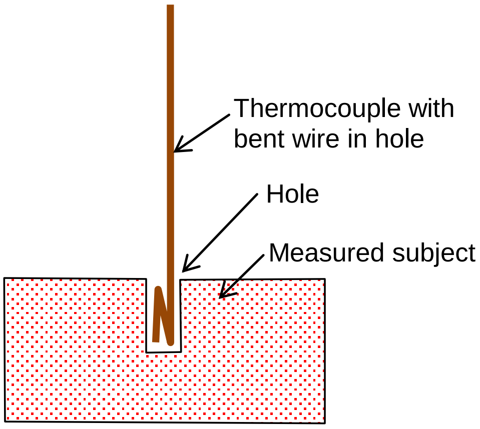

Fig. 8 Model of thermocouple with bent wire

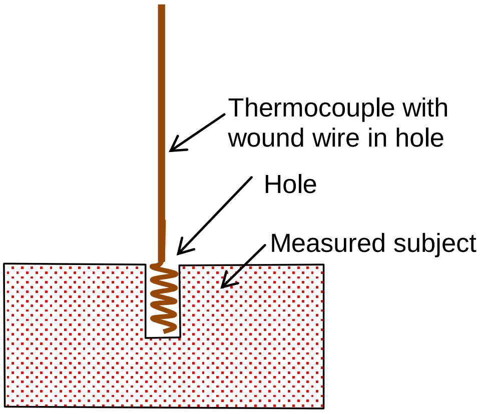

Fig. 9 Model of thermocouple with wound wire

IV. EXPERIMENT

We examined the measuring error of the proposed method of non-contact temperature measurement using a thermocouple placed in a hole. Figs. 10 and 11 depict the model and top view of the experimental apparatus; the experimental apparatus was similar to the calculation model shown in Fig. 2. The measured subject was a cylindrical copper block with a diameter of 10 mm and a length of 70 mm. The copper block was surrounded by a rock wool thermal insulator and heated to 150°C by heaters. The actual temperature of the copper block was measured by soldered T-type thermocouples with diameters of 0.2 mm. The T-type thermocouple can be used to measure temperatures up to 300°C, but is more accurate than a K-type thermocouple at low temperatures. There was a hole 4 mm in diameter and 30 mm deep at the center of the copper block. The T-type thermocouple 0.2 mm in diameter and 25 mm in length was inserted into the hole without coming into contact with the copper block. The measured steady temperature of the experimental apparatus was the average value of more than three times experiments under atmospheric conditions. The accuracy and resolution of the thermometer were 1.0 ℃ and 0.01 ℃, respectively.

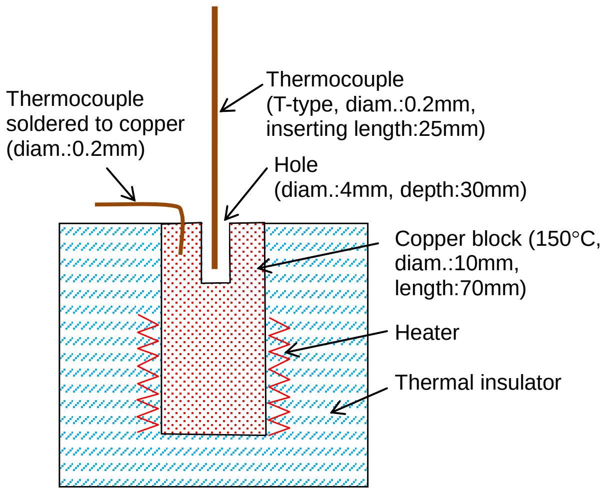

Fig. 10 Model of experimental apparatus

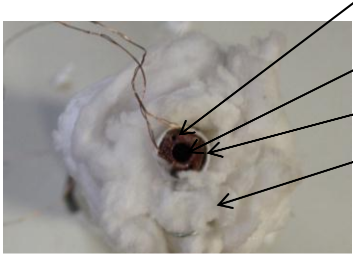

Fig. 11 Top view of experimental apparatus before insertion of thermocouple in hole

Experimental results revealed that the average temperature of the thermocouple in the hole was 143.2 ± 2°C, and the measuring error was 6.8 ± 2°C. We calculated the measuring error of typical experimental condition by using the analytical method described above. Calculation indicated a measuring error of 8°C. The experimental result and calculation were in agreement, within ± 20% error.

V. SUMMARY

We numerically and experimentally studied the measuring error of a non-contact temperature measurement method using a thermocouple placed in a hole in a measured subject. The following results were obtained:

(1) The measuring error of the proposed method of non-contact temperature measurement using a K-type thermocouple placed in a hole with a depth of 20 mm in a 1000°C subject was 2°C; this is much less than the measuring error of 14°C for a simple non-contact temperature measurement method using a thermocouple placed near the 1000°C subject.

(2) The measuring error of the proposed method of non-contact temperature measurement using a thermocouple placed in a hole of a 1000°C subject was less than 1°C when the thermocouple in the hole was longer than 22 mm, or the diameter of thermocouple was less than 0.15 mm. The measuring error decreased for the high-temperature subject under atmospheric conditions.

(3) Steady temperature was measured with an experimental apparatus similar to that in the calculation model; the experimental result was in agreement with the calculation.

REFERENCES

[1] S. Hirasawa, S. Kieda, T. Watanabe, T. Torii, T. Takagaki, and T. Uchino, "Temperature Distribution in Semiconductor Wafers Heated in a Vertical Diffusion Furnace," *IEEE Trans. on Semiconductor Manufacturing*, vol. 6, pp. 226-232, 1993.

[2] T. Watanabe, T. Torii, S. Hirasawa, and T. Takagaki, "Radiation Thermometry of Silicon Wafers in a Diffusion Furnace for Fabrication of LSI," *IEEE Trans. on Semiconductor Manufacturing*, vol. 4, pp. 59-63, 1991.

[3] T. Barry, G. Fuller, and K. Hayatleh, "Infrared Temperature Measurement for Remote Monitoring in Cold Climates," *Measurement Science Technology*, vol. 23, no. 114001, pp. 1-6, 2012.

[4] M.N. Medvedev and A.M. Medvedev, "Instruments for Non-Contact Measurement of Temperature," *Glass and Ceramics*, vol. 45, pp. 452-458, 1988.

[5] I.R. Fothergill, "Non-Contact Temperature Measurement using Forced Air Convection," *Temperature Measurement 1975 (papers from European Conference on Temperature Measurement)*, Institute of Physics in Association with American Institute of Physics, New York, pp. 409-414, 1975.

[6] Y. Toyoda, T. Seo, and T. Iuchi, "Non-Contact Temperature Measurement of Silicon Wafers based on the Combined use of Transmittance and Radiance," *Measurement*, vol. 51, pp. 393-399, 2014.

[7] S. Periyannan and K. Balasubramaniam, "Multi-Level Temperature Measurements using Ultrasonic Waveguides," *Measurement*, vol. 61, pp. 185-191, 2015.

[8] "Non-Contact Type Roller Surface Thermocouples, C015 Series," *Technical information of Chino*, Co. Ltd., Tokyo, available from https://www.chino.co.jp/english/products/sensors/c015.html (accessed 2015.3).

[9] "JSME Data Book: Heat Transfer," 5th ed., Maruzen Co., 2009.

Shigeki Hirasawa is Ph.D. from Department of Physical Engineering, Tokyo Institute of Technology, Japan. He is working as Professor in Kobe University, Japan. His area of research is thermal engineering and heat transfer in manufacturing process.

Hiroyuki Ageishi is M.Eng. from Department of Mechanical Engineering, Kobe University, Japan.

Tsuyoshi Kawanami is Ph.D. from Department of Mechanical Engineering, Hokkaido University, Japan. He is working as Associate Professor in Kobe University, Japan. His area of research is thermal engineering, refrigeration and air conditioning.

Katsuaki Shirai is Ph.D. from Faculty of Electrical and Computer Engineering, Dresden University of Technology, Germany. He is working as Assistant Professor in Kobe University, Japan. His area of research is flow measurement and laser diagnostics.