

Technical Paper

Non-contact Wafer Temperature Measurement Method with UV Light

Koji Shio

Hideyuki Wakai

Kazuhiko Kubota

Hironori Akiba

Recently, the demands for temperature measurement of silicon wafers in the semiconductor manufacturing process have risen strongly. In the low-temperature vacuum process between room temperature and about 200°C, however, a commercially viable temperature measurement method has not been established yet due to various problems. A challenge was made to establish a wafer temperature measurement method in this field. In order to accomplish this, a new temperature measurement method was developed using the reflection of p and s polarization in a UV light, which is a novel method that has not been tested before. Together with this, its effectiveness was verified. This paper introduces the finding from the aforementioned verification that the new method is capable of measuring the temperature of silicon wafers and of removing the impacts of an oxide film on the silicon wafer.

Key Words: Wafer, Temperature, Measurement, Ultraviolet ray, Non-contact, Polarization

1. Introduction

Komatsu is conducting research, development and commercialization of various temperature control equipment for the semiconductor industry. In this field, needs to accurately measure silicon wafer temperature are very strong. Noting such needs, research was conducted for the development of products to measure temperature.

A commercially viable method to measure the temperature of silicon wafers in the low-temperature vacuum process between room temperature and about 200°C had not yet been established, thus commercialization of this temperature measurement method was selected as a target.

At present, the infrared radiation thermometer is the only available measuring means. However, in the low-temperature vacuum process, the emissivity of silicon is extremely low in the infrared region and measurement cannot be taken at present due to the very low accuracy when the wafer temperature drops below 200°C. For this reason, a temperature measurement method using a polarization analysis method and a temperature measurement method using an interference method are also

proposed in lieu of the infrared radiation thermometer. The former method requires a bulky system and a long measuring time and is not commercialized yet. The latter method too can show only relative temperature variations. Additionally, methods that use Raman scattering or a sound wave are proposed. All of them, however, have problems and have not been commercialized yet. It was thought that an entry into the wafer temperature measurement field in the low-temperature vacuum process would be feasible if these problems were solved.

Noticing that direct transition levels of silicon, E1 and E2, were in the ultraviolet region, we proposed a new measurement principle and targeted the commercialization of a practical temperature measurement method using this principle. In general, direct transition levels of materials greatly affect absorption and refraction of light and can be easily captured as variations of light signals in the neighborhood of this wavelength. The direct transition level of silicon is decided by the crystal structure of silicon and is naturally affected by tempera-

ture. A method was developed radiating an ultraviolet ray in the neighborhood of the E1 level onto a silicon wafer, separating the reflection light into p and s polarizations and measuring their optical intensities.

It was found that all measured values by an oxide film deposited on a silicon wafer could be corrected when more than one measuring wavelength was used.

This paper reports this measurement principle and its measurement results.

2. Measurement Principle

An MDF model was proposed by Adachi regarding the dielectric function ϵ of silicon and this model is often used in the spectropolarization analysis method.¹⁾ The model expression of it is given below.

$$\epsilon(\omega) = e_1(\omega) + e_2(\omega) + e_3(\omega) + e_4(\omega) + e_5(\omega) + e_6(\omega)$$

where ω is an angular frequency and e_1 to e_6 , values defined by the following expressions. (Unit: [eV])

$$E[eV] = \frac{1}{1.6021892 \times 10^{-19}} \frac{h\omega}{2\pi} \quad X_1 = \frac{E + iG_1}{E_1}$$

$$X_{2m} = \frac{E + iG_2}{E_2} \quad X_{c1} = \frac{E + iG_2}{E_{c1}} = \frac{E + iG_2}{E_1}$$

$$E_{c1} = E_1$$

$$e_1 = -B_1 X_1^{-2} \ln(1 - X_1^2)$$

$$e_2 = \frac{B_{1x}}{E_1 - E - iG_1}$$

$$e_3 = -F \cdot X_{2m}^{-2} \ln\left(\frac{1 - X_{c1}^2}{1 - X_{2m}^2}\right)$$

$$e_4 = \frac{C_4 E_4^2}{E_4^2 - E^2 - iG_4 E \cdot E_4} \quad E_4 = E_2$$

$$e_5 = \frac{C_5 E_0^2}{E_0^2 - E^2 - iG_5 E \cdot E_0}$$

$$e_6 = \frac{C_6 E_{E1}^2}{E_{E1}^2 - E^2 - iG_6 E \cdot E_{E1}}$$

The temperature dependence of silicon of these parameters was measured in detail by Yamaguchi et al. in measurement that used spectroellipsometry.²⁾ Based on these measured values, parameter expressions setting temperature as a function by simple linear interpolation were set, as follows, to calculate the dielectric function of silicon.

$$E1 = -0.00042 T + 3.49$$

$$B1 = 0.00089 T + 6.07$$

$$G1 = 0.00000984 T + 0.0764$$

$$B1x = -0.00117 T + 1.69$$

$$E2 = -0.00033 T + 4.34$$

$$G2 = -0.0000398 T + 0.105$$

$$F = -0.0043 T + 5.25$$

$$C4 = 0.0029 T + 1.44$$

$$G4 = 0.000144 T + 0.049$$

$$E0 = -0.00042 T + 3.49$$

$$C5 = 0.000245 T + 0.0194$$

$$G5 = 0.0000232 T + 0.00755$$

$$EE1 = 5.33$$

$$C6 = 0.164$$

$$G6 = 0.077$$

The real part n (refractive index) and virtual part κ (extinction coefficient) of the complex refractive index N of silicon can be expressed as follows.

$$N = n + i\kappa \cong \sqrt{\epsilon}$$

(Magnetic permeability was set to 1). Calculation results of the refractive index and extinction coefficient when the silicon temperature is between 0°C and 200°C are shown in

Fig. 1.

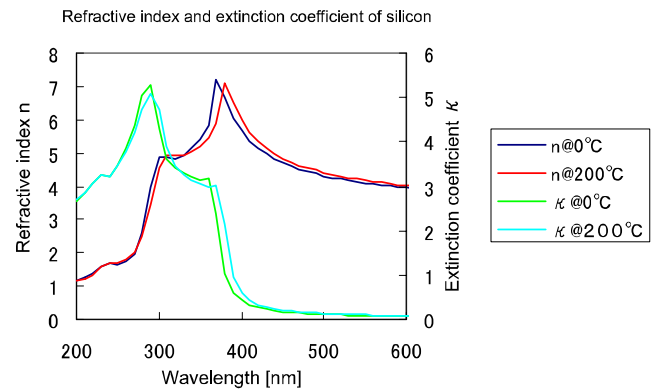


Fig. 1 Calculation results of refractive index and extinction coefficient

The calculation results show that the temperature dependence is large in the wavelength band of ultraviolet rays below 400nm. Reflectance of p polarization and s polarization when a light was injected at the angle of incidence of 70 degrees were calculated as in the general polarization analysis method. To consider the impacts of a natural oxide film deposited on an Si wafer, the following expressions were used taking multiple interferences into consideration.

$$R_p = \frac{r_{p12} + r_{p23} \exp(-2i\beta)}{1 + r_{p12} + r_{p23} \exp(-2i\beta)}$$

$$R_s = \frac{r_{s12} + r_{s23} \exp(-2i\beta)}{1 + r_{s12} + r_{s23} \exp(-2i\beta)}$$

$$\beta = \frac{2\pi n_2 d}{\lambda} \cos \theta_2 \quad \sin \theta_2 = \frac{n_1}{n_2} \sin \theta_1$$

$$r_{pa,b} = \frac{n_b^2 \cos \theta - n_a \sqrt{n_b^2 - n_a^2 \sin^2 \theta_a}}{n_b^2 \cos \theta + n_a \sqrt{n_b^2 - n_a^2 \sin^2 \theta_a}}$$

$$r_{sa,b} = \frac{n_a \cos \theta_a - \sqrt{n_b^2 - n_a^2 \sin^2 \theta_a}}{n_a \cos \theta_a + \sqrt{n_b^2 - n_a^2 \sin^2 \theta_a}}$$

where R_p and R_s are complex amplitude reflectance of p polarization and s polarization, respectively, while $r_{pa,b}$ and $r_{sa,b}$ are r_{p12} and r_{s12} when $a = 1$ and $b = 2$ and r_{p23} and r_{s23} when $a = 2$ and $b = 3$, respectively. θ_1 is an angle of incidence when the light is injected from atmosphere, θ_2 is an angle of incidence on the silicon surface in the oxide film. n_1 , n_2 and n_3 are complex refractive indexes of air, silicon oxide film and silicon, respectively.

From these expressions, the spectral reflectance of p polarization and s polarization at wafer temperatures of 0°C and 200°C can be calculated as shown in Fig. 2. The film thickness of the oxide film is calculated as 5nm.

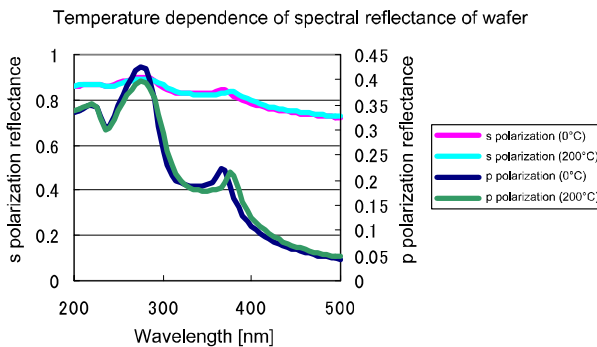


Fig. 2 Varying spectral characteristic of reflectance according to temperature

This graph shows that p polarization especially peaks at the E2 level (in the neighborhood of wavelength of 286nm) and at the E1 level (in the neighborhood of wavelength of 355nm) and that the reflectance varies greatly by temperature in these neighborhoods of wavelength.

Assuming the oxide film thickness to be 5nm, Fig. 3 is a graph plotting reflection intensities of p polarization and s polarization relative to wafer temperature in the wavelength of 365nm, at which variations seem to be relatively large, to more closely examine variations by temperature. The word “relative” is used because the graph shows relative variations from temperature 0°C to show variations by temperature better. The reflectance varies in temperature almost linearly. What is important in this graph is that p polarization varies nearly 20% in temperature variation from 0°C to 200°C, whereas s polarization varies only about 2%. This shows that measurements can be taken accurately without being affected by a variation in the optical intensity of the light source, by absorption in the optical path and other factors using the optical intensity I_s of s polarization as a reference and assuming the ratio with the optical intensity I_p of p polarization, $R = I_p/I_s$, as a measured value (Fig. 4).

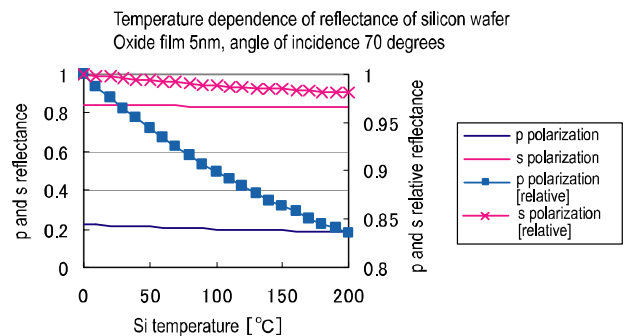


Fig. 3 Wafer temperature dependence of p and s reflectance in wavelength of 365nm

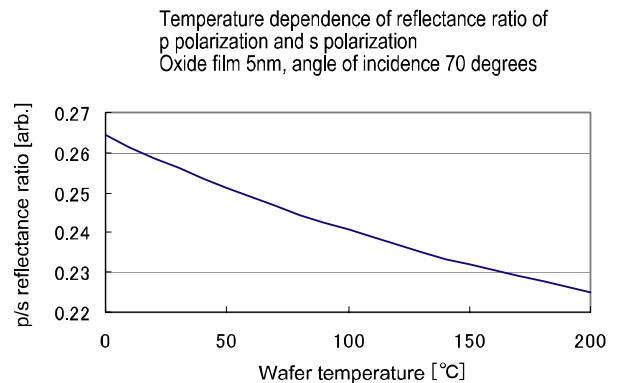


Fig. 4 Relationship between p/s polarization ratio and wafer temperature

As the graph in Fig. 2 shows, the temperature dependence of reflection intensities of p polarization and s polarization greatly differ in wavelength. For example, as shown in Fig. 5, the gradient against temperature in variation at 436nm is opposite the gradient at 365nm shown in Fig. 3.

This suggests that a method can be developed to calculate a temperature using, for example, the ratio between p polarization at 365nm and p polarization at 436nm as a measured value if the intensities of lights of two wavelengths are relatively stable. In this case, a measured value will have a larger temperature coefficient and the measurement accuracy is expected to be further improved (Fig. 6).

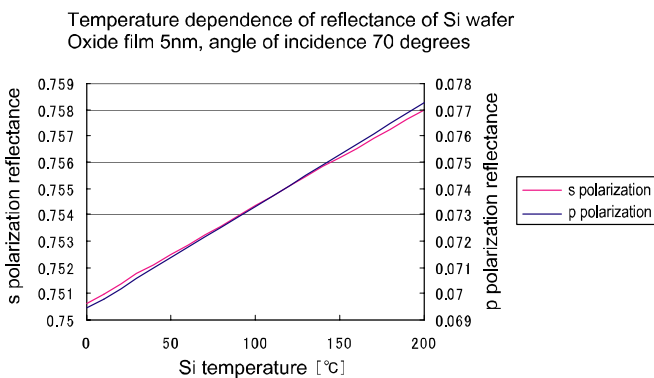


Fig. 5 Relationship between p/s polarization ratio R at 436nm and wafer temperature

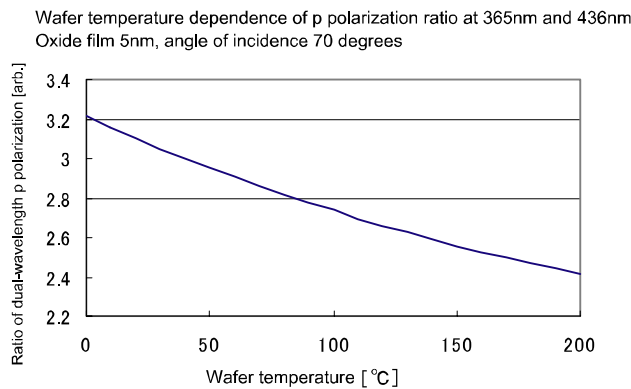


Fig. 6 Temperature characteristic of p polarization ratio at 365nm and 436nm

Utilizing the characteristic that temperature characteristics of two adjacent wavelengths have opposite codes, differences in measured values when the Si oxide film thickness is different and differences in measured values due to temperature can be separated. This is because the direction of variation in measured values due to a difference in film thickness is caused by interference and is the same even if a wavelength is slightly different unlike in temperature variation. Figure 7 shows a graph obtained when the ratio Ra of p polarization and s polarization in 365nm wavelength is plotted on the axis of ordinates and ratio Rb of p polarization and s polarization in 405nm wavelength, on the axis of abscissas. Four levels of film thickness of the oxide film were selected, namely, 10, 20, 30 and 40nm.

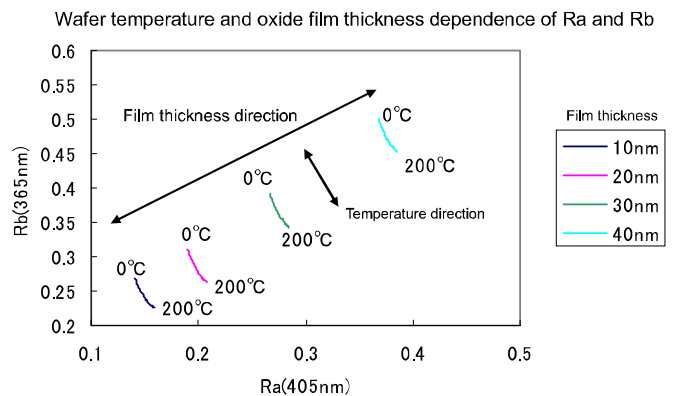


Fig. 7 Oxide film thickness and wafer temperature characteristic of reflectance ratio R

Because the direction of variation by temperature and that by film thickness differ, a two-dimensional map like this one is produced and a wafer temperature can be uniquely identified from two measured values, Ra and Rb.

3. Test Apparatuses and Test Results

Next, experiments were conducted to verify calculation results.

Layouts of the test apparatuses are outlined in **Figs. 8** and **9**.

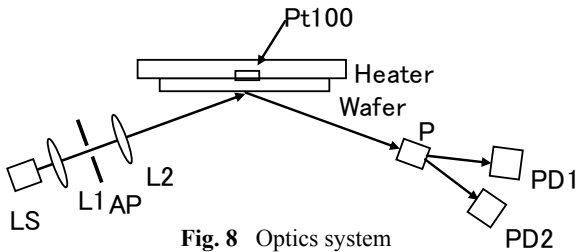


Fig. 8 Optics system

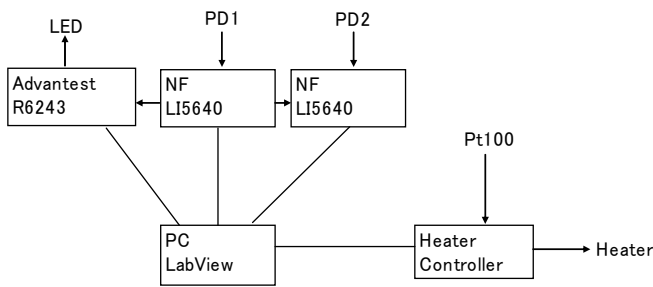


Fig. 9 Electrical system

A schematic of the optics system is shown in **Fig. 8**. Tests were conducted using a mercury vapor lamp (light of wavelength 365nm filtered by a bandpass filter) or an LED (manufactured by Nichia Corporation, center wavelength 365nm) as a light source (LS).

A light from the light source was converted into a parallel beam by a collimator (consisting of L1, AP and L2) and was injected into the wafer.

The wafer was cleaned by HF and was left with only a natural oxide film. A light reflected by the wafer was separated into p polarization and s polarization by the polarizer P and was injected into photodetectors PD1 and PD2 (photodiodes S1226 manufactured by Hamamatsu Photonics KK).

When LEDs are used, both the quantity of light and center wavelength vary when temperature varies. Temperature was controlled to room temperature (about 23 to 25°C) ±0.1°C by a Peltier device.

Wafer temperature was changed by heating using a heater. The wafer temperature was measured using a platinum resistance thermometer sensor (Pt100) inserted between the wafer and heater.

The electrical system of the measuring apparatuses is illustrated in **Fig. 9**. Signals of PD1 and 2 were input into a lock-in amplifier (model LI5460 manufactured by NF Corporation). A reference signal of the lock-in amplifier was input

into the power supply unit (model R6243 manufactured by Advantest Corporation and LEDs were driven at the same frequency. The signals of PD1 and PD2 thus acquired were retrieved by a personal computer using measurement software LabView.

The results of measurements taken by the measuring apparatuses are described below.

First, measurement was taken using a mercury vapor lamp as a light source. Variation of the ratio R of p polarization and s polarization to wafer temperature is shown in **Fig. 10**.

The axis of abscissas plots the wafer temperature (measured values of a platinum resistance thermometer sensor). The axis of ordinates was normalized using measured values of R at a wafer temperature of 60°C as “1”. The black squares denote measured values and the solid line indicates calculated values (thickness of oxide film 3nm). Variation of R by temperature was smaller with measured values than with calculated values. The differences may be explained by the oxide film thickness that was estimated by calculation, an error in the actual angle of incidence of the light into the wafer in the actual system of measurement and errors in adjustment such as alignment of the polarization planes.

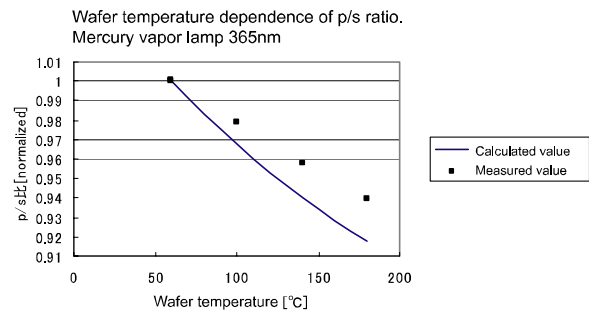


Fig. 10 Relationship between wafer temperature and p/s polarization ratio R (Light source: mercury vapor lamp)

Next, results in the measurement of variations of p polarization, s polarization and ratio R between p polarization and s polarization are plotted in **Fig. 11** when an LED was used as a light source and wafer temperature was varied in a step shape from 30°C to 120°C.

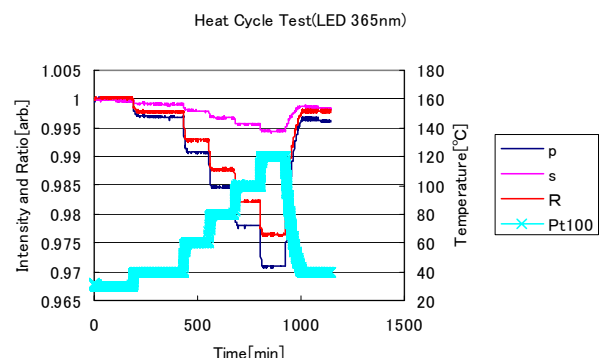


Fig. 11 Heat cycle test (Light source: LED)

The graph in Fig. 11 shows that p, s and R all vary in good harmony with wafer temperature. Figure 12 shows a graph plotting the wafer temperature on the axis of abscissas and ratio R, on the axis of ordinates based on the results obtained above.

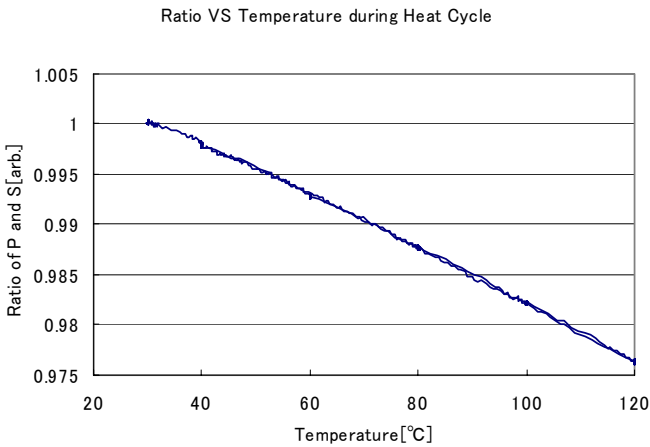


Fig. 12 Relationship between wafer temperature and ratio R (Calibration curve)

To ascertain reproducibility, a heat cycle test was conducted again on the following day. Figure 13 compares the wafer temperature measured by a platinum resistance thermometer sensor with measured values, which were obtained by converting the ratio R measured at the same time, into wafer temperature from the calibration curve of the previous day. The axis of abscissas plots time, while the axis of ordinates on the left plots wafer temperature and axis of ordinates on the right, difference between measured values of wafer temperature and the temperature calculated from ratio R.

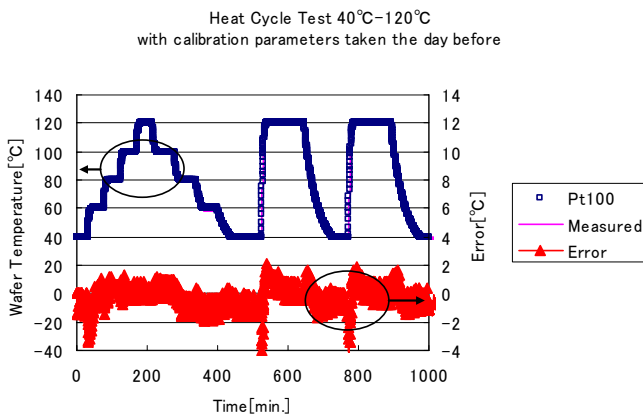


Fig. 13 Results of heat cycle test (Following day)

The values measured by a platinum resistance thermometer sensor and values converted into temperature from measured values R had good reproducibility. Differences were generally about $\pm 2^{\circ}\text{C}$ or less and values well matched. The differences became large where the wafer temperature rose rapidly. The platinum resistance thermometer sensor was installed between the wafer and heater. It is therefore believed that the heater temperature and wafer temperature did not balance when the temperature fluctuated suddenly and that what the platinum resistance thermometer sensor was actually measuring was heater temperature.

Examining the gradient in the graph in Fig. 12, variations of the p/s ratio to the wafer temperature were smaller compared with the previous test with a mercury vapor lamp. As a cause for this, the LED had broad spectral line even if the center wavelength was 365nm and the small variation of the p/s ratio was potentially affected by it. Calculations were made to confirm if there was any difference between the wafer temperature and p/s ratio R when a spectral expanse was considered (LED) and spectral expanse was 0nm (monochromatic light), as shown in Fig. 14.

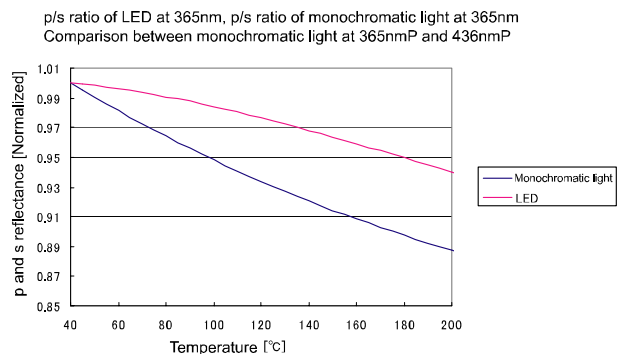


Fig. 14 Calculation results of impacts of spectral expanse

Calculated variations of the p/s ratio R to temperature were also small when a spectral expanse was taken into consideration. Therefore, the difference between a mercury vapor lamp and LED in the relationship of the wafer temperature and p/s ratio R can be attributed to a spectral broadness.

Lastly, the relationship between the wafer temperature and p/s ratio R when the oxide film thickness was also varied was measured to correct any deviation in measured values caused by the thickness of an oxide film on the wafer.

As the light source, measurement was taken using mercury vapor lamps in two wavelengths of 365nm and 405nm. Three levels of the oxide film thickness were used in the measurement, namely, natural oxide film (up to 3nm), about 10nm and about 25nm. The measurement results are shown in Fig. 15.

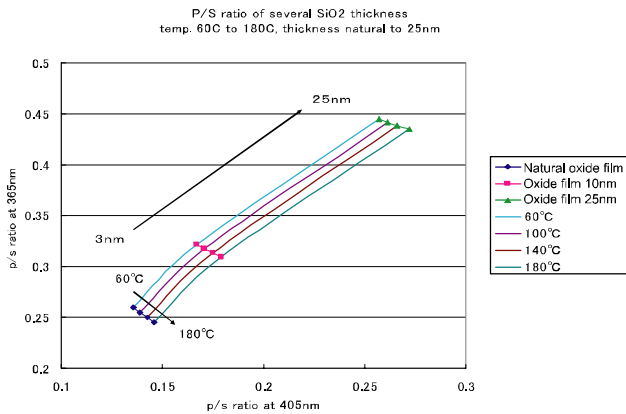


Fig. 15 Measurement results using wafers with different oxide film thickness

The axis of abscissas in the graph plots the p/s ratio R at 405nm and the axis of ordinates, the p/s ratio at 365nm. The variation due to the oxide film flows in an upper right direction and variation due to temperature, in a lower right direction. This trend is the same trend as that forecasted in calculation earlier. This means that both wafer temperature and oxide film thickness can be determined by ascertaining the locations of measured values R in two wavelengths in the graph. Thus, it could be confirmed that it would be possible to measure wafer temperature without receiving impacts of the film thickness on measured values.

4. Conclusion

A non-contact method to measure wafer temperature was devised and demonstration of the method was made through theoretical verification and actual measurement. The demonstration showed that temperature could be measured as explained in theory and that impacts of the oxide film could be removed. Additionally, the following knowledge could be gained.

- A measurement accuracy of up to about $\pm 2^{\circ}\text{C}$ would be achieved if an LED is used as a light source.
- A light source with a wide spectral band such as an LED would reduce the variation of signal (ratio between p polarization and s polarization) to the wafer temperature. A measurement accuracy of $\pm 1^{\circ}\text{C}$ or better would be possible if a mercury vapor lamp with a narrow spectral band width is used.

5. Acknowledgement

We deeply thank Professor Tomuo Yamaguchi (retired), Dr. Jan Mistrik (transferred) and Mr. Mitsuru Aoyama of the Electrical Research Laboratory of Shizuoka University, who were co-researchers, for their valuable advice and guidance

beginning the theory verification phase and for their cooperation during the initial verification tests.

References:

- 1) S. Adachi, "Model dielectric constants of Si and Ge", Am. Phys. Soc. Phys. Rev. B, Vol. 38-18, 12966, (1988)
- 2) Zhong-Tao Jiang, T.Yamaguchi, Mitsuru Aoyama and Takahisa Hayashi, "Possibility of simultaneous monitoring of temperature and surface layer thickness of Si substrate by insitu spectroscopic ellipsometry", Jpn. J. Appl. Phys., 37[2], pp. 479-483(1998)

Introduction of the writer



Koji Shio

Entered Komatsu in 1990.
Currently assigned to the Construction & Mining Equipment Innovation Center 3, Research Division.



Hideyuki Wakai

Entered Komatsu in 1976.
Currently assigned to the Construction & Mining Equipment Innovation Center 2, Research Division. Doctor of Engineering



Kazuhiko Kubota

Entered Komatsu in 1989.
Currently assigned to the Industrial Machinery Research Department, Research Division.



Hironori Akiba

Entered Komatsu in 1980.
Currently assigned to the Industrial Machinery Research Department, Research Division.

[A few words from the writer]

As the integration of semiconductor devices advances, the level of temperature management of the semiconductor process is becoming more stringent year after year. Temperature management has become a very important element from the standpoint of reducing the cost including lowering of the fraction defective. Against this backdrop, verification of a principle and demonstration of an in-situ temperature measurement method of wafers in a low-temperature vacuum process, for which an effective method has been lacking and nearly no research has been conducted, was accomplished. It is hoped that this technology will contribute to further advances in semiconductor manufacturing technology.