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A COMBINED METHOD OF NONCONTACT TEMPERATURE MEASUREMENT FOR SILICON WAFERS

Y. Toyoda/Presenter, T. Seo, and T. Iuchi

School of Engineering, Toyo University, Saitama, Japan, gn1100183@toyo.jp

Abstract: This paper presents a non-contact temperature measurement method for silicon wafers with combined utilization of transmittance technique at low temperature and radiation thermometry at high temperature because wafers are semitransparent at temperatures less than 600 °C and opaque at more than that. In this method, we utilize polarization technique and the *Brewster angle* between air and dielectric films that are grown on silicon wafers. The measurements are performed at the same geometrical arrangement and unaffected by dielectric film thicknesses. As a result, the combined method is widely applicable at temperatures from room to more than 1000 °C for silicon wafers.

Keywords: Transmittance, Emissivity, Polarization, Dielectric film, Silicon wafer.

1. INTRODUCTION

A non-contact temperature measurement is strongly required for silicon semiconductor manufacturing processes such as rapid thermal processing to produce high quality products of silicon wafers [1~2].

As silicon wafers are semitransparent at relatively low temperatures below 600 degrees Celsius and at longer wavelengths that corresponds to the band gap energy, E_g of silicon, and opaque at shorter wavelengths corresponding to the energy, E_g as well, a noncontact method of temperature measurement that covers the wide temperature range is very difficult [3~4].

In the present paper, we studied a non-contact temperature measurement method that combined the temperature dependence of transmittance below 600 °C and radiation thermometry over 600 °C. The combined method utilized polarization technique (use of p-polarization) and the *Brewster angle* between air and dielectric films such as SiO_2 or Si_3N_4 grown on silicon wafers.

For a semitransparent wafer, the measurement of p-polarized transmittance at the wavelengths of 1.20 and 1.30 μm enabled the temperature measurement from room to 600 degrees Celsius. For an opaque wafer, the p-polarized radiation thermometry at the wavelength of 4.5 μm succeeded the temperature measurement above 600 °C. The combined temperature measurement method with the use of transmittance and radiation is valid for silicon wafers irrespective of the variations of dielectric film thicknesses and resistivities due to dopant concentrations, and moreover this method is immune to background radiation noise originated from intense heating lamps in a manufacturing process.

2. TEMPERATURE MEASUREMENT BASED ON TRANSMITTANCE

Fig. 1 shows a model of light transmittance consisting of a silicon wafer on which a dielectric film (SiO_2 or Si_3N_4) is grown, where n_1, n_2 and n_3 are the refractive indices of air, the film and the silicon wafer, respectively.

The transmittance of a silicon wafer decreases with increasing temperature because incident light interacts with free carriers induced inside the wafer with increasing temperature [5~6].

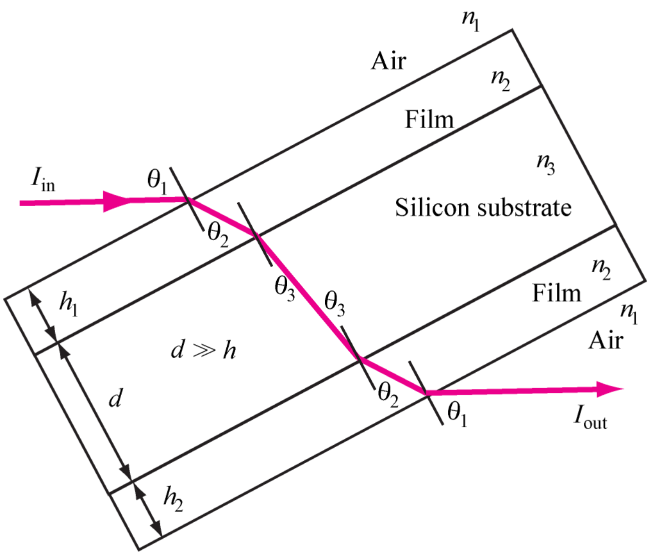

Fig. 1 A light transmittance model for a silicon wafer on which a dielectric film is grown.

The p-polarized intensity ratio of the transmitted and incident light, I_{out}/I_{in}, is presented in Eq. (1), which is referred to the transmittance, $\tau_p(T)$, as a function of temperature, T, of the wafer [6].

$$\tau_p(T) = \frac{I_{out}}{I_{in}} = S(\theta_1)(1-R)^2 \exp[-\frac{\alpha(T)d}{\cos\theta_3}], \quad (1)$$

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 = n_3 \sin\theta_3, \quad (2)$$

where $S(\theta_1)$ is the transmittance of the dielectric film, and $\alpha(T)$ is the absorption coefficient of the silicon substrate at the relevant wavelength at temperature, T. R is the power reflection coefficient at the silicon surface.

In Eq. (1), a practical light path length is assumed to be $d/\cos\theta_3$ because of $d>>h$.

Since both $S(\theta_1)$ and R are only very weak functions of temperature, the p-polarized transmittance is normalized as $\mathrm{N}\tau_p(T)$ as shown in Eq. (3),

$$\mathrm{N}\tau_{\mathrm{p}}(T) = \frac{\tau_{\mathrm{p}}(T)}{\tau_{\mathrm{p}}(T_{\mathrm{r}})} = \exp[-\{\alpha(T)-\alpha(T_{\mathrm{r}})\}\frac{d}{\cos\theta_3}], \qquad (3)$$

where T_r is the room temperature [8].

From Eq. (3), the difference, $\Delta\alpha(T) = \alpha(T) - \alpha(T_r)$, of the absorption coefficients between temperature, T and the room temperature, T_r, is expressed as shown in Eq. (4).

$$\Delta\alpha(T) = -\frac{\cos\theta_3}{d}\{\ln\tau_{\mathrm{p}}(T) - \ln\tau_{\mathrm{p}}(T_{\mathrm{r}})\}. \qquad (4)$$

Fig. 2 shows the experimental apparatus for the transmittance measurement of a silicon wafer [6]. The light beam, I_{in}, from a tungsten lamp or a semiconductor laser is collimated and chopped mechanically or electrically, and is incident to a silicon wafer. The transmitted light, I_{out}, through the wafer is detected by an infrared detector. A lock-in amplifier is used to recover the transmitted signal without disturbance from radiation inside the furnace.

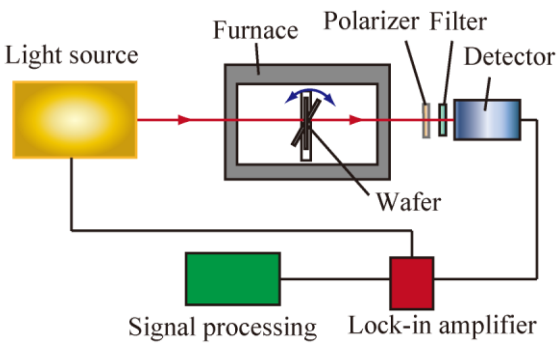

Fig. 2 Experimental set up for transmittance measurement.

In the previous study, we obtained that the p-polarized spectral transmittance remained constant irrespective of dielectric layer thickness at an angle θ=55° for SiO_2 film and θ=63° for Si_3N_4 film, respectively [5~6]. These angles are known as the *Brewster angles* between air and the dielectric films and expressed as shown in Eq. (5),

$$\theta_1 = \tan^{-1}\left(\frac{n_2}{n_1}\right) \qquad (5)$$

Based on these results, the temperature dependence of the p-polarized transmittance of silicon wafers were measured using the apparatus in Fig. 2. A large number of n-type (100) plane silicon wafers were used for the experiments.

Fig. 3 shows an example of experimental relations between temperature and p-polarized transmittance at θ_1=63° and λ=1.30 μm, where the characteristic curves of all specimens with resistivities between 0.1 and 2000 Ωcm were overlapped in the temperature range from 400 to 600 °C. Similar relations also hold for silicon wafers with dielectric layers such as SiO_2 or Si_3N_4 films.

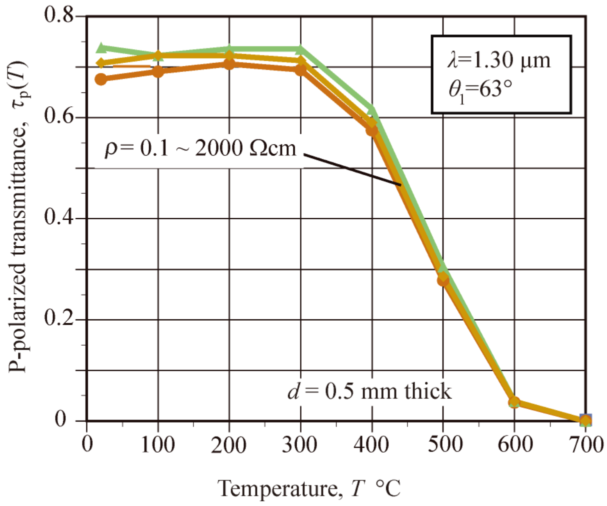

Fig. 3 Experimental relation between temperature and p-polarized transmittance for silicon wafers with different resistivities (ρ=0.1~2000 Ωcm, θ_1=63° and λ=1.30 μm).

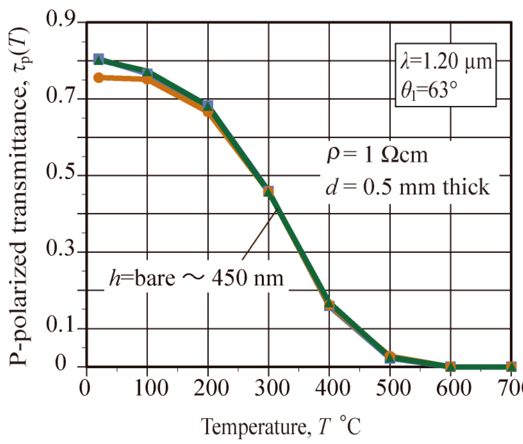

Fig. 4 Experimental relation between temperature and p-polarized transmittance for silicon wafers with different layer thicknesses (h=0~450 nm, θ_1=63° and λ=1.20 μm).

Fig. 4 shows another example of experimental relations between temperature and p-polarized transmittance at θ_1=63° and λ=1.20 μm, where the characteristic curves of all specimens with different layer thicknesses of Si_3N_4 films (h=bare ~450 nm) were overlapped in the whole temperature range from room to 600 degrees Celsius. Similar relations also hold for silicon wafers with different layer thicknesses of SiO_2 films at θ_1=55°.

We can see from Figs. 3 and 4 that the temperature measurement by the p-polarized transmittance at the Brewster angles is valid for the temperature range between room and 600 °C with use of two wavelengths at 1.20 and 1.30 μm.

Fig. 5 shows experimental results of the difference, $\Delta\alpha(T)=\alpha(T)-\alpha(T_r)$, of absorption coefficients between temperature, T, and room temperature, T_r, as a function of temperature at the wavelengths of λ=1.20 and 1.30 μm that are calculated using the data obtained in Figs. 3 and 4.

A non-contact temperature measurement of semitransparent silicon wafers can be realized below 600 degrees Celsius when the transmittance measurement is performed at wavelengths of λ=1.20 and 1.30 μm.

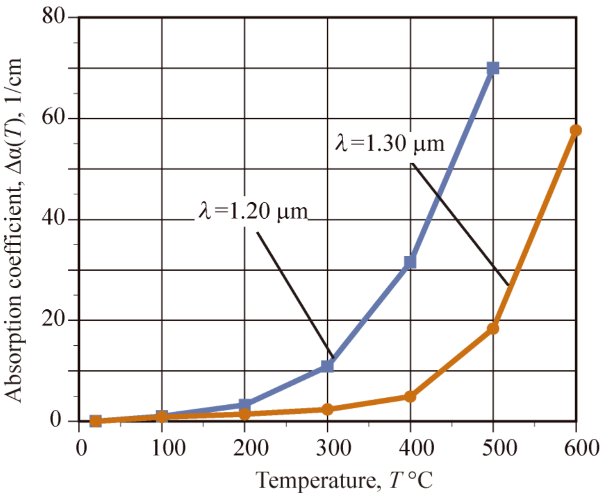

Fig. 5 Experimental results of difference, $\Delta\alpha(T)$, of absorption coefficients of silicon wafers as a function of temperature, T, (Eq. (3)).

3. EMISSIVITY-INVARIANT RADIATION THERMOMETRY

Silicon semiconductor becomes opaque at a temperature above 600 °C or at shorter wavelengths than the one corresponding to the band gap energy (E_g=1.12 eV at room temperature) [3].

We found out an emissivity-invariant condition that the p-polarized emissivity at a *Brewster angle* remained constant irrespective of dielectric film thicknesses and resistivity variations due to impurity doping concentration and temperature [8].

Fig. 6 shows the experimental setup used to measure the directional polarized radiance and emissivity of a specimen, which consists of a polarized radiometer that measures polarized radiance signals at angles ranging from the normal to 80° and a hybrid surface temperature sensor that intermittently monitors the surface temperature of the wafer [9]. A silicon wafer is heated and maintained at a high temperature of above 600 °C. The surface temperature, T, is monitored by the hybrid surface temperature sensor, and the p- and s-polarized radiance signals are simultaneously measured by the radiometer, and finally directional p- and s-polarized emissivities are calculated.

Fig. 7 shows an example of experimental results of polarized emissivities of silicon wafers with SiO_2 films at a *Brewster angle* of θ_1=55° and a wavelength of λ=1.55 μm. While s-polarized emissivities vary with increasing layer thickness, h, p-polarized emissivities remain constant. We call this property of p-polarized emissivity at a *Brewster angle* as " Polarized emissivity-invariant condition".

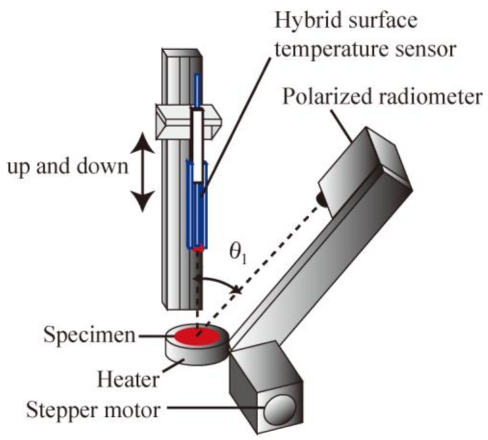

Fig. 6 Experimental setup used to measure directional polarized radiance and emissivity of silicon wafers.

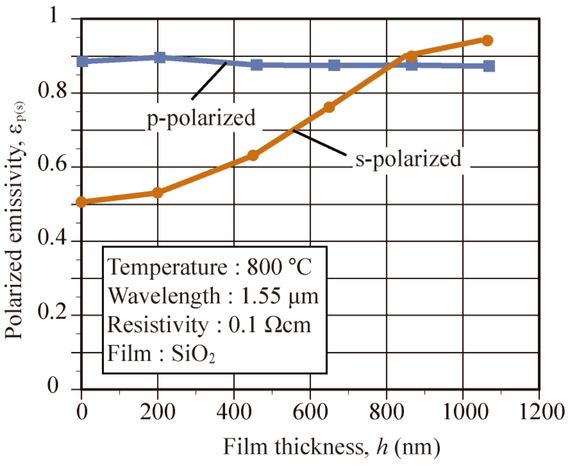

Fig. 7 Experimental relations between film thickness and polarized emissivity of silicon wafers with SiO_2 layer at λ=1.55 μm.

A large number of n-type (100) plane silicon wafers were used for the experiments for radiation thermometry as well as the transmittance experiments.

Fig. 8 shows experimental results for the p-polarized emissivities of silicon wafers with different SiO_2 film thicknesses and different resistivities as a function of angle, θ_1. The invariant point of p-polarized emissivities are observed at θ_1=55° irrespective of wide variations of film thickness, h, as well as resistivity, ρ.

Similarly, Fig. 9 shows experimental results for the p-polarized emissivities of silicon wafers with different Si_3N_4 film thicknesses and different resistivities. The invariant point for them are obtained at θ_1=63° in spite of large variations of layer thickness, h, and resistivity, ρ, as well.

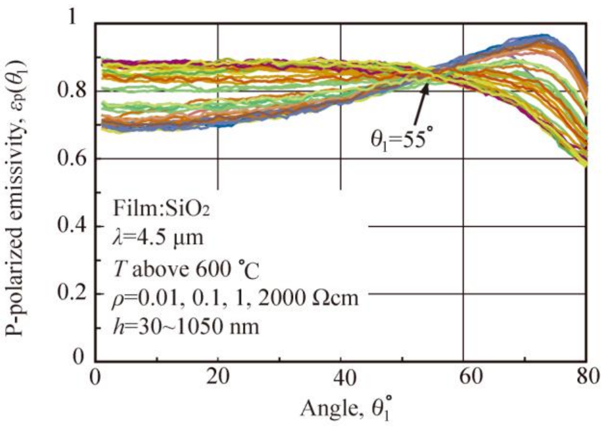

Fig. 8 Experimental results for p-polarized invariant points for silicon wafers with SiO_2 films at λ=4.5 μm.

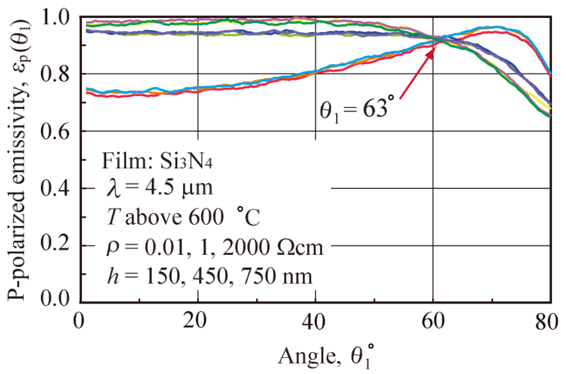

Fig. 9 Experimental results for p-polarized invariant points for silicon wafers with Si_3N_4 films at λ=4.5 μm.

4. CONBINED NON-CONTACT TEMPERATURE MEASUREMENT

We studied transmittance measurement and radiation thermometry for silicon wafers. Based on these results, we propose a combined method of non-contact temperature measurement that could measure the temperature in the wide range from room to above 1000 ºC.

Fig. 10 shows a cut away view of a combined non-contact temperature measurement system with a lamp heating process such as RTP [2, 4]. The geometrical arrangement of the combined method is the prominent feature of the system. When the temperature of a silicon wafer is below 600 degrees Celsius, the temperature measurement is carried out by the transmittance measurement, while at higher temperature above 600 ºC under an opaque condition, radiation thermometry is applied. In both conditions, the utilization of p-polarization and a *Brewster angle* is indispensable for this method.

In order to mitigate intense background noise originating from a manufacturing process, a lock-in amplifier is used for the transmittance measurement, while for radiation thermometry, a polarized radiometer responsive to a wavelength of 4.5 μm can completely avoid radiation noise coming from fiercely intense heating lamps [10].

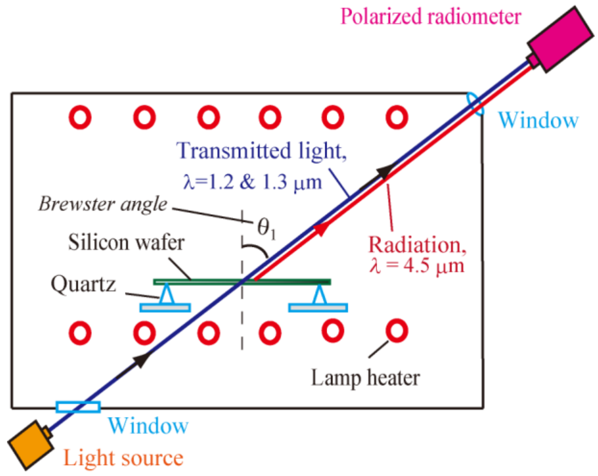

Fig. 10 Schematic of a combined non-contact temperature measurement method.

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