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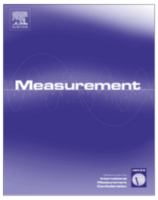

Non-contact temperature measurement of silicon wafers based on the combined use of transmittance and radiance

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ABSTRACT

We propose a non-contact temperature measurement method that combines the temperature dependence of transmittance below 600 °C and radiation thermometry above 600 °C. The combined method uses a polarization technique and the *Brewster angle* between air and a dielectric film such as SiO_2 or Si_3N_4 grown on silicon wafers. A prominent feature of this method is that both measurements of transmittance and radiance are performed with the same geometrical arrangement.

For a semitransparent wafer, the measurement of p-polarized transmittance at the wavelengths of 1.1, 1.2 and 1.3 μm enables temperature measurement in the range from room temperature to 600 °C. For an opaque wafer above 600 °C, the p-polarized radiation thermometry at the wavelength of 4.5 μm allows the temperature measurement without the emissivity problem. The combined method with the use of transmittance and radiance is valid in the entire temperature range irrespective of variations of film thickness and resistivity.

1. Introduction

An effective non-contact temperature measurement technique is urgently required for silicon manufacturing processes, such as rapid thermal processing (RTP), in order to produce high quality silicon wafer products [1–5]. Such wafers have complex optical properties. For example, they change with temperature, when thin films are grown on their surfaces, with changing dopant concentrations, and for other reasons. Additionally, depending on the band-gap energy of the silicon wafer, they become semitransparent at low temperatures and opaque at high temperatures [6–13]. These properties cause difficulties when it is necessary to conduct non-contact temperature measurements.

Previously, radiation thermometry has been the primary method for conducting temperature measurements on silicon wafers at temperatures exceeding 600 °C, which is the point where they become opaque [5,14–17], while the temperature dependence of the transmittance, or the absorption edge wavelength shift caused by the band-gap energy, have been utilized for temperature measurements at below 600 °C, where such wafers become semitransparent [18–21].

In this paper, we propose a non-contact temperature measurement method that combines the temperature dependence of transmittance below 600 °C and radiation thermometry above 600 °C. The combined method uses a polarization technique and the *Brewster angle* between air and a dielectric film, such as SiO_2 or Si_3N_4, grown on silicon wafers. A prominent feature of this method is that both the transmittance and radiance measurements are performed with the same geometrical arrangement, which contributes to the construction of a simple measurement system.

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For a semitransparent wafer, p-polarized transmittance measurements at wavelengths of 1.1, 1.2, and 1.3 µm enable temperature measurements ranging from room temperature to 600 °C. For measurements of opaque wafers exceeding 600 °C, the use of p-polarized radiation thermometry at the wavelength of 4.5 µm allows the measurements without the emissivity problem [22]. The use of the combined transmittance and radiance method is valid over the entire temperature range, irrespective of dielectric film thickness variations.

Since it is unaffected by the background radiance inevitably generated from the intense heating lamps, this method shows promise for use in a number of applications related to the silicon wafer manufacturing process.

2. Temperature measurement based on transmittance

Fig. 1 shows a light transmittance measurement model for a silicon wafer composed of a silicon substrate (thickness: d) and a dielectric film (thickness: h) such as a silicon dioxide (SiO_2) or a silicon nitride (Si_3N_4), where n_1, n_2, and n_3 are the refractive indices of air, the film, and the substrate, respectively.

The intensity ratio of the transmitted and incident light, I_{out}/I_{in}, is presented in Eq. (1), which is referred to as the transmittance, $\tau(T)$, as a function of temperature, T, of the wafer [23–24].

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

$$S(\theta_1) = \frac{p_3}{p_1}\frac{t_{12}^2 t_{23}^2}{1 + r_{12}^2 r_{23}^2 + 2r_{12}r_{23}\cos\beta}, \tag{2}$$

$$r_{12} = \frac{p_1 - p_2}{p_1 + p_2}, \tag{3}$$

$$t_{12} = \frac{2p_1}{P_1 + p_2}, \tag{4}$$

with analogous expressions for r_{23} and t_{23}.

$$\beta = \frac{2\pi}{\lambda_0} n_2 h \cos\theta_2, \tag{5}$$

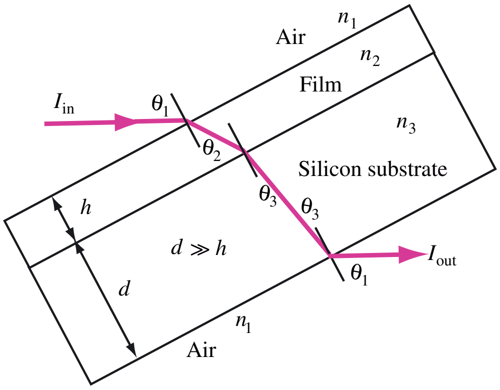

Fig. 1. Model of light transmittance measurement for a silicon wafer with a dielectric film.

where r_{ij} and t_{ij} are reflection and transmission coefficients, respectively, between surfaces i and j (i, j = 1, 2, 3). $S(\theta_1)$ is the transmittance of the dielectric film and $\alpha(T)$ (=$4\pi\kappa/\lambda_0$) is the absorption coefficient of the substrate at the relevant wavelength at temperature T, κ is the extinction coefficient of the substrate. R is the reflectance at the substrate. β is the phase delay of an electromagnetic wave inside a film of thickness h and λ_0 is the wavelength in vacuum. In Eq. (1), a practical light path length is assumed to be $d/\cos\theta_3$, which neglects h because of $d \gg h$.

For p-polarized light,

$$p_j = \frac{\cos\theta_j}{n_j} \quad (j = 1, 2, 3), \tag{6}$$

for s-polarized light,

$$p_j = n_j \cos\theta_j \quad (j = 1, 2, 3), \tag{7}$$

and

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 = n_3 \sin\theta_3, \tag{8}$$

When $\theta_1 + \theta_2 = \pi/2$ holds, r_{12} in Eq. (3) for p-polarized light becomes zero in connection with Eq. (8), which leads to

$$\theta_1 = \tan^{-1}\left(\frac{n_2}{n_1}\right). \tag{9}$$

This angle is known as the *Brewster angle* between the two media, namely air (n_1) and the dielectric film (n_2) [25].

The p-polarized transmittance $S(\theta_1)$ of the dielectric film can then be expressed as

$$S(\theta_1) = \frac{p_3}{p_1} t_{12}^2 t_{23}^2. \tag{10}$$

Eq. (10) shows that the p-polarized transmittance of the film is independent of the film thickness, h, because the term $\cos\beta$ disappears. This implies that the p-polarized transmittance, $\tau_p(T)$, of a silicon wafer remains unaffected by the film thickness when the transmittance measurement is performed at the Brewster angle derived in Eq. (9). We refer to this condition as the p-polarized invariant-transmittance condition.

Then, the p-polarized absorption coefficient, $\alpha_p(T)$ cm^{-1}, is determined from Eq. (1) as a function of temperature as shown in Eq. (11).

$$\alpha_p(T) = -\frac{\cos\theta_3}{d}\left\{\ln\tau_p(T) - \ln S(\theta_1)(1-R)^2\right\}. \tag{11}$$

Since both $S(\theta_1)$ and R are functions of refractive indices n_1, n_2 and n_3 that are less sensitive to temperature [26–28], these quantities become only very weak functions of temperature. Then the p-polarized normalized transmittance, $\tau_{pN}(T)$=$\tau_p(T)/\tau_p(T_r)$, can be expressed as Eq. (12) instead of Eq. (11) [19].

$$\tau_{pN}(T) = \frac{\tau_p(T)}{\tau_p(T_r)} = \exp\left[-\{\alpha_p(T) - \alpha_p(T_r)\}\frac{d}{\cos\theta_3}\right], \tag{12}$$

where T_r is the room temperature (25 °C for example).

From Eq. (12), the p-polarized normalized absorption coefficient, $\alpha_{pN}(T)$=$\alpha_p(T)$-$\alpha_p(T_r)$, is expressed as follows: