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EFFECTS OF REFLECTIVE SURFACES ON SILICON EMISSIVITY AND TEMPERATURE MEASUREMENTS

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ABSTRACT

The effects of front-side reflective surfaces on the emissivity and temperature measurement of silicon wafers in a Rapid Thermal Processing chamber with backside heating are examined through optics modeling. Two schemes are contrasted. In (1), the pyrometry detector looks at the back-side of the wafer; in (2), it looks at the front-side of the wafer. In both cases, the temperature errors occur when the reflector's reflectivity deviates from unity. However, the error dependence on the reflector reflectivity exhibits interesting differences in these two schemes. Under the working conditions proposed in this paper, a non-ideal reflector introduces a bigger temperature error in the "backside-detector" scheme than in the "front-detector" scheme. Practical implications of these results are also discussed.

INTRODUCTION

Correct measurement of the temperature of wafers in real time is critical to RTP applications. When pyrometry is used, the emissivity must be measured *in-situ* for accurate results. It is well known that, at high temperatures, the wafer is opaque and one can determine the wafer emissivity (ε_w) from the wafer reflectivity (R_w), using $\varepsilon_w = 1 - R_w$. The wafer temperature can then be measured *in-situ*, as wafer radiation and reflectivity can be measured simultaneously with ripple techniques with a single detector [1, 2]. However, at lower temperatures (e.g., <700°C), the wafer becomes transparent, i.e, its transmission (Tr_w) is non-zero. As a result, we have $\varepsilon_w = 1 - R_w - Tr_w < 1 - R_w$, i.e., the emissivity measured by reflection experiment alone includes an error term equal the transmission of the wafer. As an example, Fig. 2 plots the calculated emissivity error at various temperatures for a lightly doped silicon wafer. The wafer is double-side polished, 0.65 mm thick, and the probe wavelength is 2.5 μm. Using formula developed by McMahon [3], the calculation is based on the experimental results of the emissivity measurement of a 1.77 mm thick silicon crystal [4]. Clearly, significant emissivity errors occur as the actual temperature decreases below 600°C. Below 520°C, the error even exceeds the true emissivity. Depending on the wafer temperature and probe wavelength, such emissivity errors can introduce significant temperature errors. In this paper, we examine, through optics modeling, the effects of reflective surfaces on the temperature measurement. Generally, the reflective surfaces lead to higher *measured* wafer radiation and higher *measured* wafer reflection, resulting in improved temperature measurement. In both arrangements examined below, the temperature error is reduced to zero when the reflective surfaces are ideal.

The schematic drawings of the two arrangements are shown in Fig. 1. In both cases, the wafer is heated from the backside, and a reflective surface with reflectivity R_m is placed above the wafer. In the "back-side detector" scheme (Fig. 1.(a)), the pyrometer looks at the back-side of the wafer and measures the reflected lamp radiation in addition to the wafer radiation from the back-side. In the "front-side detector" (Fig. 1(b)), the pyrometer measures the radiation from the front side of the wafer only, with no reflection measurement performed. The "front-side detector" scheme has been previously considered in applications of temperature sensing of metal surfaces [5]. The reflections from the surface behind the lamps are ignored in the modeling. Generally, these reflections should make the environment surrounding the wafer more like a blackbody and thus make the emissivity error smaller.

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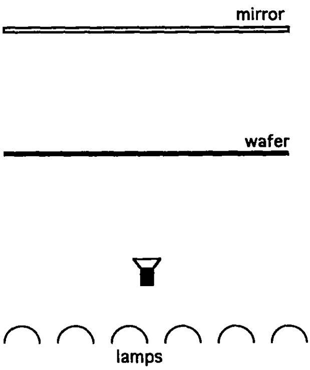

Fig. 1(a) Schematic drawing of the "back-side detector" scheme.

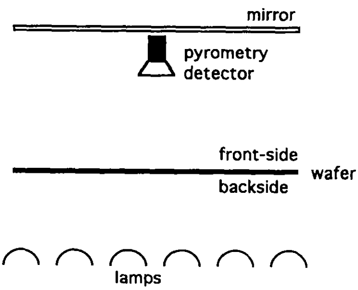

Fig. 1(b) Schematic drawing of the "front-side detetor" scheme.

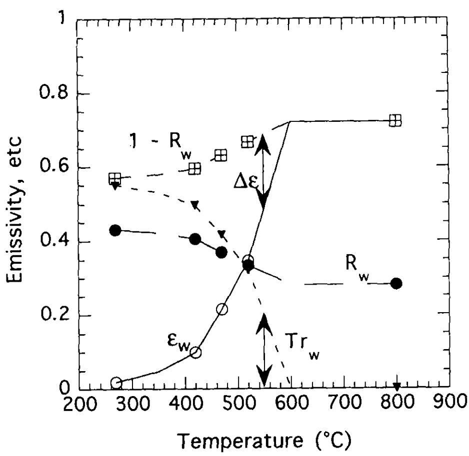

Fig. 2. Calculated silicon wafer emissivity (ε_W), reflectivity (R_W), transmission (Tr_W), assumed emissivity ($1 - R_W$) and emissivity error ($\Delta\varepsilon = 1 - R_W - \varepsilon_W = Tr_W$) at various temperatures. The wafer is lightly doped, double-side polished, with a thickness of 0.65 mm. The probe wavelength is 2.5 μm.

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MODELING

In this simplified model, the leakage of lamp light around the edge of the wafer is neglected; and the wafer is assumed to be double-side polished. Also, the wafer and reflector are assumed to be smooth enough that all the reflections between the wafer and the reflector are specular. A detector wavelength bandwidth wide enough to avoid the interference effects between the wafer and the mirror has been assumed. Only light rays normal to the wafer surfaces are considered (1-D model). In experiments, this condition can be approximately realized by adding a focused collimating lens in front of the detector.

We will use the following notations:

ε_w = wafer emissivity;
R_w = wafer reflectivity;
Tr_w = wafer transmission;
ε_{eff} = effective emissivity of wafer in the presence of the reflector;
R_{eff} = effective reflectivity of wafer in the presence of the reflector;
R_m = the reflectivity of the reflector (mirror);
T = true wafer temperature;
λ = wavelength of radiation;
$\Delta\varepsilon$ = emissivity error;
ΔT = temperature error = true temperature - measured with inaccurate emissivity.

As alluded to earlier, the "back-side detector" scheme with no reflectors, using the ripple technique to measure the wafer reflection, works well at high temperatures, when the wafer is opaque. At low temperatures (<700°C) and a wavelength > 1.3 μm, the approach suffers because the wafer is no longer opaque. In this case, placing a reflective surface on the top of the wafer as shown in Fig. 1(a) will increase both the measured radiation and the measured reflectivity of the back-side of the wafer. The measured radiation increases because some of the radiation from the front-side of the wafer is reflected back through the wafer. Likewise, the measured reflectivity also increases since some of the light transmitting through the wafer will be reflected back through the wafer.

Obviously, the presence of the reflector increases the radiation measured by the detector. In fact, the measured radiation includes the radiation from the wafer surface facing the detector, and that from the other side of the wafer reflected back by the reflector. The first term is proportional to ε_w. Since all reflections between the reflector and the wafer are specular, the second term can be found to be proportional to $\frac{R_m Tr_w}{1-R_m R_w}\varepsilon_w$. The $\frac{R_m Tr_w}{1-R_m R_w}$ term results from multiple reflections, such as in the Fabry-Perot interference calculations. The effective reflectivity (R_{eff}) can be calculated in a similar way. Thus, the effective emissivity (ε_{eff}) as measured by the detector and the effective reflectivity (R_{eff}) are:

$$\varepsilon_{eff} = \varepsilon_w + \frac{\varepsilon_w R_m Tr_w}{1-R_m R_w} \quad (1)$$

$$R_{eff} = R_w + \frac{R_m Tr_w^2}{1-R_m R_w} \quad (2)$$

If the mirror is ideal (R_m =1), we have $\varepsilon_{eff} + R_{eff} = 1$, or, $\varepsilon_{eff} = 1 - R_{eff}$, even when the wafer is not opaque. Since the reflectivity can be measured with the ripple techniques, the effective emissivity can then be measured *in-situ*. However, when the reflector is not ideal, or, R_m <1, such a method will introduce an error term $\Delta\varepsilon = 1 - R - \varepsilon_{eff} = \frac{1-R_m}{1-R_m R_w} Tr_w$. As we

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will see in the next section, at low temperatures (400 – 500°C), the resulting temperature error can be very sensitive to the quality of the reflector.

The effective emissivity of the wafer–reflector system in the "front-side reflector" scheme can be found in a very similar way. We assume that the effects of the presence of the pyrometer on the reflections will be negligible, and that the reflector is cold. Due to the multiple reflection between the wafer and the reflector, the measured radiation increases with the addition of the reflector. It can be shown that

$$\varepsilon_{eff} = \frac{\varepsilon_w}{1-R_w R_m} . \qquad (3)$$

If the wafer is opaque and the reflector is ideal, or, $Tr_w = 0$, $R_m = 1$, we have a very simple result: $\varepsilon_{eff} = 1$. Under these conditions, the emissivity can be known without additional reflection measurement. When $R_m < 1$, we have an error term $\Delta\varepsilon = \frac{R_w(1-R_m)}{1-R_w R_m}$. Compared with the "back-side detector" scheme, the advantage of this scheme is obvious: it does not need the reflection measurement. The disadvantage is that to have the wafer opaque, the wavelength must be restricted to be short (~ 1.0 μm) at low temperatures. When the lamp interference is negligible, it has been demonstrated that pyrometry measurements at 1 μm can be performed down to 400°C [6].

In the next section, we will numerically calculate the temperature error due the emissivity error as the reflector reflectivity deviates from unity. For practical considerations, the pyrometry wavelengths will be different for the two schemes. For the "back-side detector" scheme, the reflectivity will be simultaneously measured by ripple technique. Thus, a long pyrometry wavelength (2.5 μm) is chosen to improve the signal/noise ratio at low temperatures (400°C – 500°C). For the "front-side detector", it is required that the wafer be opaque. Thus, a short pyrometry wavelength (1.0 μm) is chosen. In calculations for both cases, the same silicon wafer is used: 0.65 mm thick, lightly doped. The emissivities for such silicon wafers are converted from the experimental data on lightly doped silicon crystals with a thickness of 1.77 mm [4].

RESULTS AND DISCUSSIONS

Fig.3 (a) shows the emissivity error of a 0.65 mm thick silicon wafer versus the reflector reflectivity in the "back-side reflector" scheme. The pyrometry wavelength is 2.5 μm. If the actual wafer temperature is assumed to be 420°C, the emissivity error ($\Delta\varepsilon$) increases from 0 to 0.15 as the reflector reflectivity decreases from 1.0 to 0.8. Similar calculations were also performed for various wafer temperatures. From these emissivity errors, the temperature errors (ΔT) were found by calculating what effects the emissivity error would have on a pyrometry measurement at a given λ and T. The results are shown in Fig. 3(b). It is interesting to note that when the mirror reflectivity is close to 1, ΔT is nearly proportional to $1-R_m$. In addition, ΔT increases as wafer temperature decreases, when the wafer becomes more transparent. Overall, these results indicate that the temperature error is quite sensitive to the reflector quality. For example, as R_m drops to 0.8, for a wafer with a thickness of 0.65 mm and a temperature of ~500°C, a temperature error of 20°C will occur if $1 - R_{eff}$ is used as the true emissivity. Given R_m, ΔT depends on the true wafer temperature as well as pyrometry wavelength.

The results for the "front-side detector" scheme are shown in Fig. 4. Fig.4 (a) shows the emissivity error of the wafer versus the reflector reflectivity. The pyrometry wavelength is 1.0 μm. In this case, the wafer is opaque. As a result, the emissivity error $\Delta\varepsilon$ is independent of the wafer temperatures. For R_m between 0.8 and 1, the absolute values of emissivity error

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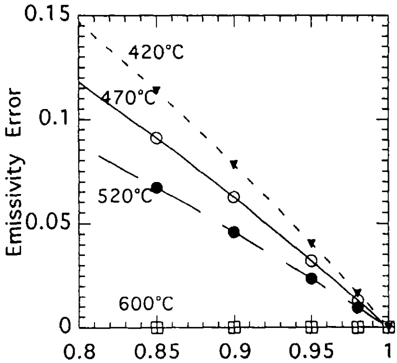

Fig. 3(a) Emissivity error vs. the reflector reflectivity in the "back-side detector" scheme for various temperatures.
Pyrometry wavelength = 2.5μm.

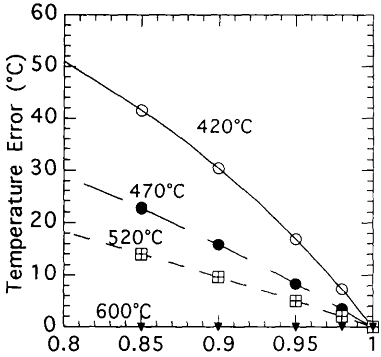

Fig. 3(b). Temperature error vs. reflector reflectivity in the "back-side detector" scheme, at different wafer temperatures.
Pyrometry wavelength = 2.5μm.

$\Delta\varepsilon$ are larger than those as measured with the "back-side detector" scheme at temperatures over 520°C, and are smaller at temperatures lower than 470°C.

Fig.4 (b) shows the temperature error ΔT at various wafer temperatures when the reflector reflectivity deviates from 1.0 to 0.8. It is interesting to note that in this scheme the temperature error is slightly bigger when the wafer temperature is higher. More interestingly, at low temperatures (420°C - 500°C), the temperature error ΔT as measured from the "front-side detector" scheme is much smaller than that from the "back-side detector" scheme. This observation can be explained by two reasons. First, at low temperatures (420°C - 500°C) the emissivity measured in the "back-side detector" scheme is much smaller than unity, while that measured in the "front-side detector" scheme is very close to unity. For example, at 420°C and $R_m = 0.8$, the emissivity measured in these two schemes is 0.16 and 0.91, respectively. Meanwhile, the emissivity error ($\Delta\varepsilon$) measured in the "back-side detector" scheme is larger than that in the "front-side detector" scheme. Thus, the relative error of emissivity $\Delta\varepsilon/\varepsilon$ is considerably smaller in the "front-side detector" scheme. It is $\Delta\varepsilon/\varepsilon$, rather than $\Delta\varepsilon$, that determines the temperature error (ΔT). Second, for practical reasons, the wavelength in the "back-side detector" schemes (2.5 μm) is considerably longer than that in the "front-side detector" scheme (1.0 μm). It follows from the formula of black-body radiation that given $\Delta\varepsilon/\varepsilon$, ΔT is larger at a longer wavelength.

Overall, the above results indicate that 1) the presence of a reflector in both schemes improves the measurement accuracy of wafer emissivity and temperature significantly; 2) the accuracy of emissivity and temperature measurement of silicon wafers is quite sensitive to the quality of reflector. Under the conditions proposed in this paper, the "back-side detector" scheme works in long wavelengths (2.5 μm), while the "front-side detector" scheme works in short wavelengths (1 μm) and gives smaller ΔT. These conclusions are drawn under idealized assumptions, which are yet to be tested in real systems. For example, in addition to a series of idealistic assumptions listed in the previous section, it is assumed that in the "front-side detector" scheme the lamp light is completely blocked at the edge of the wafer so that the detector only detects the wafer radiation. Despite these simplifications, we believe that our

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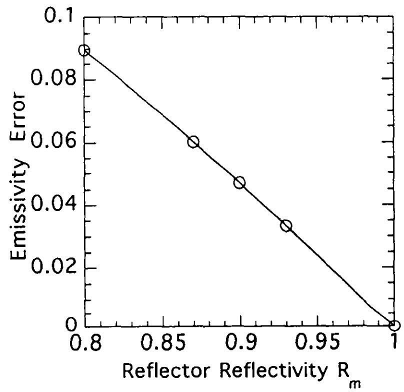

Fig. 4(a). Emissivity error vs. the reflector reflectivity in the "front-side detector" scheme. Pyrometry wavelength = 1.0μm. Results are independent of temperatures.

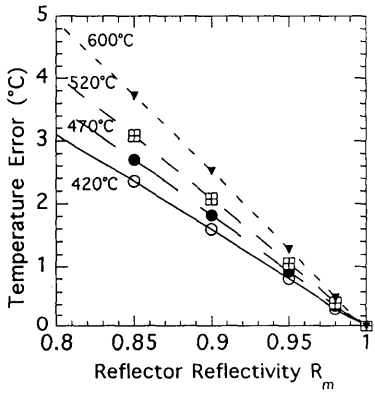

Fig.4 (b) Temperature error vs. reflector reflectivity in the "front-side detector" scheme, at different temperatures. Pyrometry wavelength = 1.0 μm.

results are of practical relevance for the development of real RTP systems and clearly have demonstrated the importance of the reflector quality.

CONCLUSION

In two temperature measurement schemes, the measured emissivity errors ($\Delta\varepsilon$) and temperature error (ΔT) of silicon wafers are calculated under idealized conditions through optics modeling. These errors are found to be very sensitive to reflector qualities. Given a non-ideal reflector, the "front-side detector" scheme gives smaller ΔT. Practical implications are also discussed. Support from SRC is gratefully acknowledged.

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