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Rapid Thermal and Integrated Processing IV

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LOW TEMPERATURE (≥ 400 °C) SILICON PYROMETRY AT 1.1 μm WITH EMISSIVITY CORRECTION

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ABSTRACT

In this work we have examined the experimental low-temperature limits of 1.1μm pyrometry for the measurement of the temperature of silicon wafers and aluminum-coated silicon wafers at temperatures under 700 °C in RTP chambers. In-situ emissivity correction in the same range has also been demonstrated with a single detector for radiation and reflection measurements. Temperatures as low as 450 °C have been measured on metallized surfaces with an accuracy of better than 10 °C without any a priori knowledge of the wafer emissivity.

INTRODUCTION

While there are many potential Rapid Thermal Processing (RTP) applications in the 400 - 700°C range, the measurement of the wafer temperature in this temperature range is very difficult. At "long" wavelengths, such as 1.5 or 3 μm, below 700 °C wafers of lightly-doped silicon become partially transparent, so that by reflection measurements alone one cannot establish the emissivity. At "short" wavelengths (e.g. ≤ 1.1 μm), the substrate remains opaque, making emissivity measurement easier. However, the weak wafer radiation at these wavelengths under 700 °C makes pyrometry difficult, especially if significant lamp radiation in the same wavelength range is present. (In principle, because of the AC component of the heating lamps, one can correct for the effect of lamp heating upon radiation measurements [1]. However due to the extreme relative weakness of the radiation at low temperatures, this approach is not feasible in two-sided heating systems much below 700 °C.)

In this work we have experimentally investigated the low-temperature limits of pyrometry at 1.1 μm. We have done our work without the presence of interference from heating lamps by using a resistive heater for the wafer under study. Such an approach is technologically relevant because of the recent trend towards one-sided lamp-heating systems. In such systems, with proper shielding, it would be possible to implement pyrometry on the side of the wafer opposite that being heated to avoid excessive interference from the heating lamps. We have also implemented a system for the measurement of the wafer emissivity (of polished surfaces) at the same time as the radiation measurement. The system corrects automatically for emissivity changes as large as that from 0.65 to ~0.1.

It is well known that at temperatures under 700°C, the emissivity of lightly doped silicon wafers at wavelengths ≥ 1.2 μm drops with temperature because of the

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relatively small number of free carriers in the wafer [2]. Therefore one needs to measure transmission in addition to the reflectivity to establish the emissivity for accurate pyrometry, greatly complicating a practical system. This is not necessary at wavelengths ≤ 1.1 μm, because these photons have sufficient energy to be absorbed by valence band to conduction band transitions, making the wafer opaque in this range. A second advantage of short wavelengths is the relatively weak dependence of the temperature extracted from a pyrometry measurement on wavelength. Straightforward analysis of the radiation law shows that the relationship between the uncertainty in emissivity ($\Delta\varepsilon$) and the error in the extracted temperature (ΔT) is

$$\frac{\Delta\varepsilon}{\varepsilon} = \frac{\Delta T\, h\, c}{T^2\, k\, \lambda} \tag{1}$$

where h is Planck's constant, c is the speed of light, k is Boltzmann's constant, and λ is the wavelength. This relationship is shown in Fig. 1 for several temperatures. For example, near 600°C, to measure the temperature with an accuracy of 1°C requires a relative error of ε of ~ 0.5% at 4 μm, but only ~ 2% at 1 μm. This eases the requirement for accurate determination of the emissivity. The penalty of short wavelength pyrometry is weak radiation at lower temperatures. For example, near 600°C, the radiated power density per unit wavelength is ~ 300 times weaker than the peak near 3 μm.

EXPERIMENTAL RESULTS AND ANALYSIS

Our experiments were performed on wafers placed on a chuck heated by a resistance heater inside a water cooled vacuum chamber (Fig. 2). The radiation was observed from the polished side of the wafer through borosilicate glass windows extended away from the heater to remain cool. The "actual" temperature of each sample was measured using a thermo-couple attached to the wafer by epoxy just outside the area probed by pyrometry. The estimated error in this temperature is ± ~10°C, and is based on uncertainty in the thermocouple calibration and a possible temperature difference between the location of the thermocouple and that from which the radiation was measured.

Because emissivity depends on angle of incidence, wavelength, etc., the most reliable way to measure emissivity is to use the same sensor as that used to measure the sample radiation. One can distinguish between the wafer radiation and the reflected signal by modulating the probe beam, so that the reflected beam has a different frequency content than the radiation. The probe beam may be the lamps themselves, as in the well-known "ripple" technique [1,3]. As a probe beam we used a broadband source (tungsten lamp), which was mechanically chopped so that the reflected probe signal could be distinguished from the wafer radiation. The angle of incidence, and of the detector, was 60° from the surface normal.

Both the wafer radiation and the reflected probe signal were detected by a single silicon photodiode. The spectral width of the measurements was limited between 1.1 μm (detector cutoff) and ~0.8 μm (filter). The wafer surface was imaged onto the detector by *f*10 optics and a demagnification factor of ~0.5. The short circuit

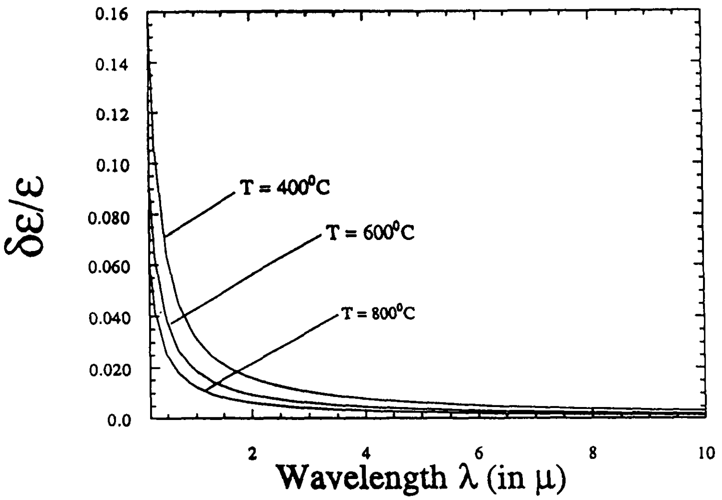

Fig. 1. Fractional accuracy in emissivity required to measure the temperature with an accuracy of 1 °C vs. wavelength for several temperatures.

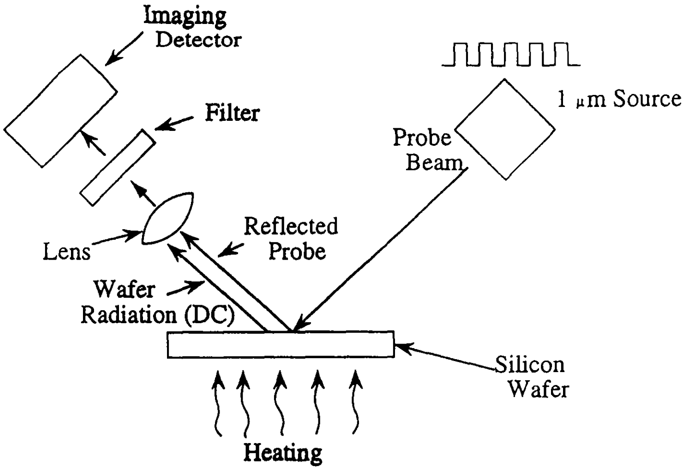

Fig. 2. Experimental apparatus used to measure reflection (for emissivity) and radiation for temperatures to 600°C.

photocurrent in the detector was converted to a photocurrent by a transimpedence amplifier. The magnitude of the reflected probe beam was measured from this signal by a lock-in amplifier using the frequency of the mechanical chopper as a reference. This value was subtracted from the DC value of the signal to yield the intensity of the wafer radiation. Measurements of the wafer radiation extracted in this way and direct measurements of the wafer radiation (i.e. with the probe beam off) yielded good agreement. The absolute value of the reflectance was set by assuming a reflectance of lightly doped polished silicon in this wavelength range and angle of incidence at room temperature of 0.35. This value was evaluated from the known index of refraction of silicon [4] at 1.2 μm and assuming unpolarized light. The reflectivity R at other temperatures and for other wafers was determined by multiplying the ratio of the measured reflected signal under those conditions to that of the silicon wafer at room temperature by 0.35.

Fig. 3 shows the detected radiation signal (arbitrary units) as a function of temperature for a lightly-doped polished silicon wafer and for a similar wafer uniformly coated with aluminum. The data was only taken in the direction of increasing temperature vs. time. Note that because of the highly reflective nature of the aluminum, its radiation was substantially below that of the bare wafer at any given temperature. The emissivity at each condition was then calculated by $\varepsilon = 1 - R$, where R is the reflectivity.

Fig. 4 shows the temperature of the aluminum-coated wafer extracted from the pyrometry measurements using an emissivity calculated three different ways. First, the room temperature emissivity of the silicon wafer (0.65) was used (referred to as "uncorrected" in Fig. 4). Because of the high reflectivity (low emissivity) of the aluminum-coated wafer, this led to a large underestimation ~50 °C) of the true wafer temperature. Second, the temperature of the aluminum-coated wafer was extracted using the measured room-temperature emissivity of the aluminum-coated wafer at all temperatures ("constant emissivity correction"). This yields a value of the extracted temperature that agrees well within the error bars for temperatures under 560 °C. At temperatures over 560°C, this method substantially overestimates the temperature, showing that the true emissivity is larger than that used in the calculation. In Fig. 4, the results for this method were only plotted for temperatures over 550 °C to avoid overlap with the points extracted using the in situ emissivity measurements.

In the third set of points in Fig. 4 (labelled "in situ emissivity correction"), at each temperature the emissivity was measured in-situ. The superiority of measuring emissivity in-situ for each point is clear. With this method, at all temperatures the temperature extracted by pyrometry agrees well with the actual wafer temperature. Furthermore, note that using 1.1 μm radiation, the temperature of an aluminum-coated wafer was accurately measured down to 450°C.

Fig. 5 shows the emissivities measured by reflection as a function of temperature for the aluminum-coated and bare wafers. Note that the emissivity of the aluminum-coated wafer is fairly constant for temperatures under 500°C, but increases sharply over 550 °C. This explains why the constant emissivity calculation of Fig. 4 overestimated the temperature above 550 ° C. Physically, at high temperatures, the aluminum began to react with the silicon substrate. This reduced the reflectivity and increased the emissivity. The reduced reflectivity could be observed by eye after the

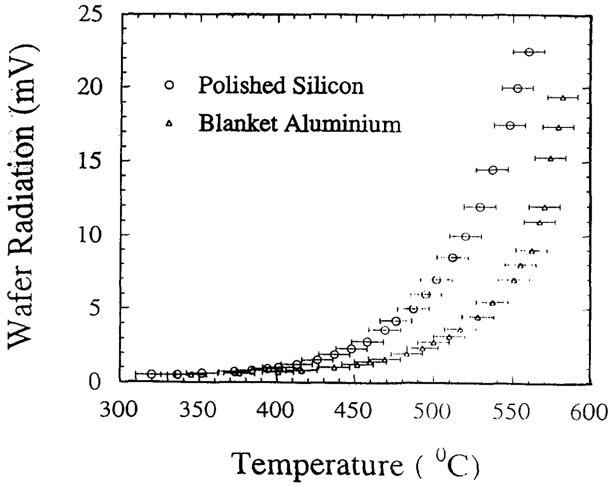

Fig. 3. Radiation vs. temperature for a polished silicon wafer and for a polished wafer coated with aluminum.

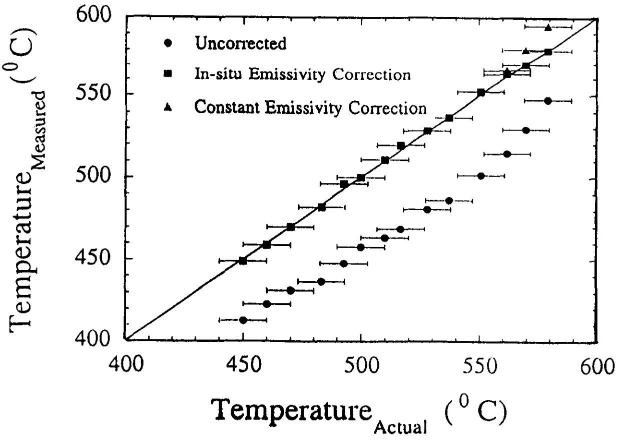

Fig. 4. Extracted temperature of the aluminum-coated wafer of Fig. 3 vs. actual temperature (mesured by a thermo-couple) by (a) assuming the room-temperature emissivity of the silicon wafer for all temperatures, (b) assuming the room-temperature value of emissivity of the aluminum-coated wafer, and (c) using the emissivity measured in situ at each temperature.

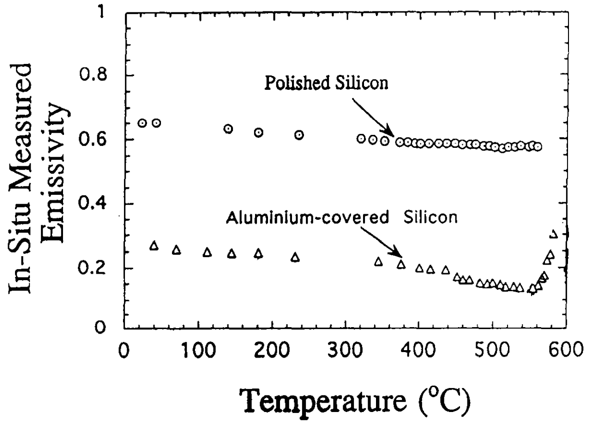

Fig. 5. Measured in-situ emissivities of bare and aluminum-coated Si wafers at an angle of incidence of 60 ° at a wavelength of 0.8 - 1.1 μm.

completion of the thermal cycle.

SUMMARY

Pyrometry at ~ 1.1 μm has been performed down to temperatures as low as 400°C on bare and aluminum-coated silicon wafers. A single detector was used for both the measurement of the wafer radiation and for the measurement of a reflected probe beam to determine the emissivity in-situ. The temperature of an aluminum-coated wafer was accurately measured without any a priori knowledge of its emissivity, and changes in the emissivity as the metal reacted with the silicon were accurately followed.

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REFERENCES

1. C. Shietinger, B. Adams, and C. Yarling, Proc. Symp. Mat. Res. Soc. **224**, 23 (1991).
2. T. Sato, Jap. J. App. Phys. **6**, 339 (1967).
3. A.T. Fiory, C.S. Schietinger, B.A. Adams, and F.G. Tinsley, Mat. Res. Soc. Symp. Proc. **303**, 139 (1993).
4. H.H. Li, J. Phys. Chem. Ref. Data **9**, 561 (1980).