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3.3μm PYROMETRY IN SINGLE SIDED RTA FROM 400-700°C USING IN-SITU MEASUREMENT OF REFLECTION AND TRANSMISSION

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ABSTRACT

Pyrometry of silicon wafers under 700°C at wavelengths over 1μm is difficult because lightly doped wafers become partially transparent. In this work, a modified commercial RTCVD reactor with 8" wafer capability was used to study the temperature measurement of Si wafers over the range of 400-700°C using top and bottom pyrometric detectors. We present initial results on measurements of both reflection and transmission *in-situ* to determine emissivity at 3.3μm. For heavily doped wafers emissivity was independent of temperature and the measured temperature by pyrometry agreed well with that measured by thermocouple for 400-700°C. For lightly doped wafers, emissivity was temperature dependent due to the increased transparency of the wafer at low temperatures. Using fixed emissivity, the measured temperature severely underestimates the actual temperature below 550°C. By calculating emissivity from the measured reflection and transmission, accurate temperature measurement was achieved from 400-700°C without any *a priori* knowledge of the wafer.

INTRODUCTION

Measuring wafer temperature in rapid thermal processing equipment is a severe problem at low temperatures (≤700°C) because of the dependence of emissivity on temperature, doping, and surface finish. In this paper, transmissivity and reflectivity are measured at a wavelength of 3.3μm using the ripple technique [1] with a top and bottom detector respectively. From this result an *in-situ* determination of emmisivity is made. Once emissivity is known, wafer temperature can be calculated from Plank's equation. It is shown that using this technique wafer temperature can be determined over the range of 400-700°C without prior knowledge of the doping level in the wafer.

DESCRIPTION OF APPARATUS

The experiments were carried out in a modified commercial RTCVD reactor with 8" wafer capability. The wafers used were 4" double-side polished and set in a SiC ring, one lightly doped and one heavily doped. Each wafer had a type K thermocouple attached for direct measurement of temperature at the same location as that measured by the pyrometer. A schematic of this apparatus is shown in Fig. 1.

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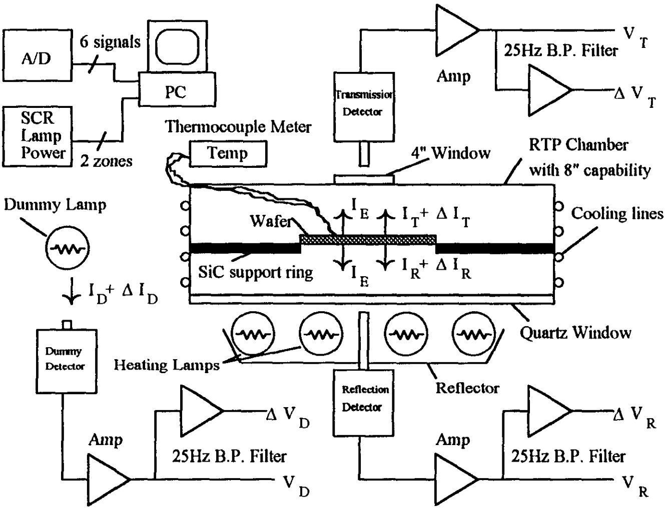

Fig. 1 Schematic drawing of apparatus used for experiments.

To heat the wafers, infrared radiation from Tungsten-Halogen lamps was introduced into the water cooled stainless steel vacuum chamber through a 27mm thick quartz window. A port at the top of the chamber was fitted with a 4" window for detecting radiation from the top side of the wafer. The chamber was maintained at a pressure of 5 Torr with a throttle valve and by flowing purge nitrogen.

The heating lamps were arranged in two zones connected in parallel for this experiment. Together there were 34 heating lamps and two "dummy lamps". The dummy lamps were mounted in separate housings. All lamps were driven by a three phase SCR power controller. Computer control was used to output a DC component, and a 25Hz AC component of the signal voltage to the SCR power controllers. The DC portion determined the power output of the lamps, while the 25Hz AC portion was used for the ripple technique in determining reflection and transmission of the wafer.

Three thermo-electrically cooled InGaAs detectors were used to sense 3.3μm infrared radiation due to an in-line band-pass filter, which included an internal lens to focus radiation onto the InGaAs diode. The first was the "dummy lamp" detector and was used to directly measure the lamp intensity independent of the wafer radiation. A second detector viewed the wafer radiation and transmitted lamp light through the port at the top of the chamber. An additional lens mounted at the end of an adjustable stainless steel tube was used to form focusing telescope for this detector. The third detector was mounted at the base of the lamp housing for detecting wafer radiation and reflected lamp light. A water cooled LiF light pipe was mounted on the detector and extended up past the lamp housing to view the wafer from the bottom. The end of the LiF light pipe also included an additional focusing lens.

The detectors produced a voltage output proportional to the incident 3.3μm light intensity. The voltage signal was amplified by an additional variable gain voltage amplifier which was connected directly to an A/D channel in the computer and also fed to a 25Hz band-pass filter. The output of the filter was connected to a different A/D channel, totaling six A/D channels required for the three detectors. The digitized signals from the variable voltage gain amplifier were continuously averaged over one period of the 25Hz signal to determine a DC value for the reflection, transmission, and dummy detectors. The digitized outputs from the 25Hz band-pass filters were analyzed by software using a quadrature technique to determine the magnitude of the 25Hz signal seen by each of the reflection, transmission, and dummy detectors.

EXPERIMENTAL PROCEDURE

All experiments were performed by stepping the lamp power from a low power setting to a high power setting and back down. The time step between power level changes was varied between 20 seconds and 200 seconds in different experiments. For long time steps, additional radiation was observed presumably due to heating of the quartz window at the bottom of the chamber. For this reason, all data presented is for 50 second steps or less. Six time varying signals determined by the computer which signify the DC portion of the reflection, transmission, and dummy detectors signals, and the magnitude of the 25Hz AC portion of the reflection, transmission, and dummy detectors signals are labeled V_D, V_R, V_T, ΔV_D, ΔV_R, and ΔV_D in Fig. 1, respectively. The values of these signals were recorded by the computer at one second time steps. At specific intervals during the experiment, values for wafer temperature were read off the thermocouple meter. Data points shown in the following figures have been determined from the detector data taken at each of these intervals.

Reflection is determined by the formula

$$R = C_R \frac{\Delta V_R}{\Delta V_D}, \tag{1}$$

where C_R is a constant of the system depending on light transmission into the detector, detector gain, and viewing area, independent of the wafer. This constant was calibrated by assuming the reflection from a heavily doped wafer equaled the theoretical value of 0.29. Transmission is given by

$$T_r = C_T \frac{\Delta V_T}{\Delta V_D}, \tag{2}$$

where C_T is a constant of the system, again independent of the wafer. This constant was calibrated by the fitting the transmission data for the lightly doped wafer to the theoretical transmission versus temperature curve. The radiation emitted from the wafer was determined by subtracting the transmitted radiation from the total radiation detected by the transmission detector at the top of the chamber. This is given by

$$I_E = C_1\left(V_T - V_D\frac{\Delta V_T}{\Delta V_D}\right), \qquad (3)$$

where C_1 is a system dependent constant which will be incorporated into the constant C_E. Once the radiation emitted from the wafer is determined, the temperature of the wafer can be calculated from Plank's equation. If one assumes the wafer temperature is much less than 4360°K (for 3.3μm) the temperature is given by

$$T(°K) = \frac{4360}{\ln\left(\varepsilon(T)C_E / I_E\right)}, \qquad (4)$$

where C_E is a constant calibrated by matching thermocouple results to pyrometer results at the highest temperature and $\varepsilon(T)$ is the temperature dependent emissivity given by

$$\varepsilon(T) = 1 - R - T_r. \qquad (5)$$

RESULTS AND DISCUSSION

Results for the 0.06cm thick heavily doped wafer, $N_D=1\times10^{19}$ cm^{-3}, showed no transmitted radiation for all temperatures, which means that when the wafer is opaque, no light from the lamps "leaks" around the wafer. Also, this means that the top detector directly measures wafer radiation for heavily doped wafers. The reflection data indicate a constant reflection at all temperatures, so a constant emissivity was assumed. The temperatures calculated from the pyrometer data compare very well with the measured thermocouple temperatures over the range of 400-700°C as shown if Fig 2.

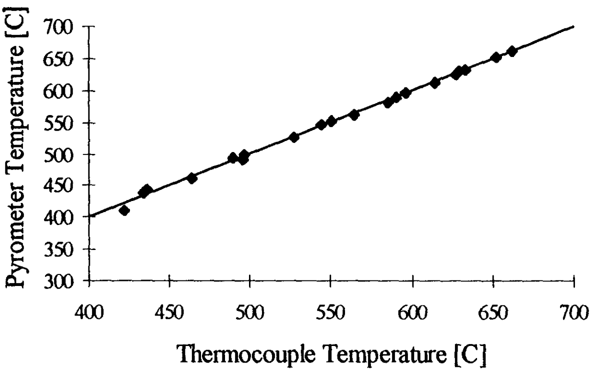

Fig. 2 Temperatures measured by pyrometery, assuming a constant emissivity, versus thermocouple temperatures for a heavily doped wafer.

If one considers next the data for a 0.06cm thick lightly doped wafer, $N_D=5x10^{14}$ cm^{-3}, and makes the same assumption of a constant emissivity, the temperatures computed by pyrometry do not compare well with the measured thermocouple temperatures below 550°C as shown in Fig. 3. This is due to the lightly doped wafer becoming partially transparent at low temperatures.

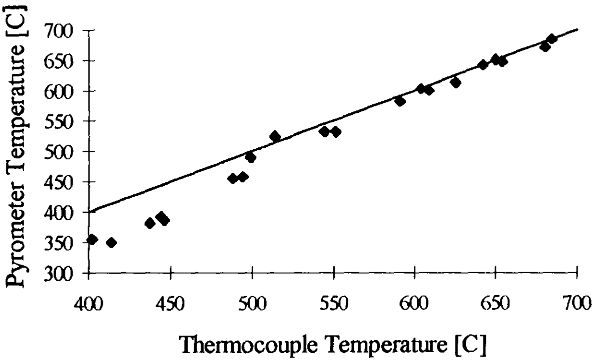

Fig. 3 Temperatures measured by pyrometery, assuming a constant emissivity, versus thermocouple temperatures for a lightly doped wafer.

In order to correct for the problem of a partially transmitting wafer, the variation of emissivity with temperature must be determined. These results are plotted as a function of temperature along with the calculated theoretical values [2] in Fig. 4.

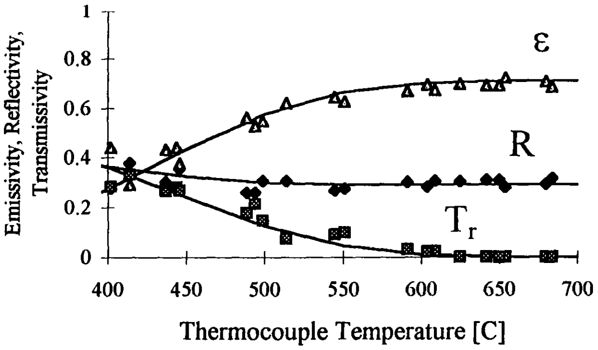

Fig. 4 Theoretical and measured values of reflectivity, transmissivity, and emissivity for the lightly doped wafer.

One can see that both reflection and transmission vary with temperature. This means that the standard arrangement of using one reflection detector for "ripple" pryrometery could not be successful in correcting the data. The temperature may now be calculated for the lightly doped wafer from emitted radiation based on Plank's equation corrected for a temperature dependent emissivity which was determined *in-situ* from reflection and transmission measurements. The results, in Fig. 5, show a much improved correspondence to the thermocouple data as compared to the uncorrected results of Fig. 3.

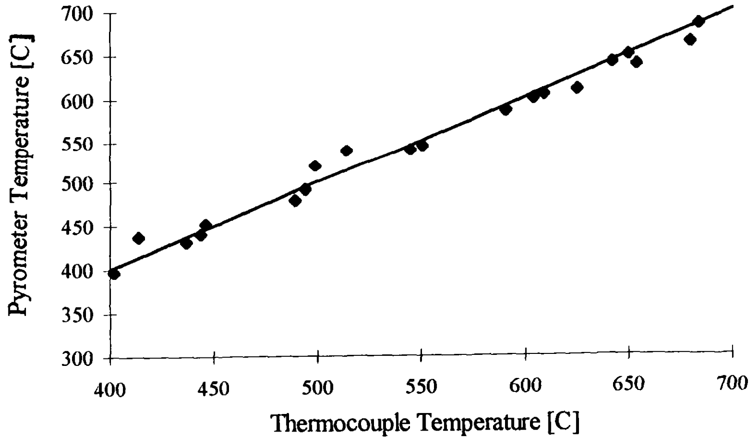

Fig. 5 Temperatures measured by pyrometry, using emissivity data of Fig. 4, versus thermocouple temperatures for a lightly doped wafer.

CONCLUSION

An enhanced ripple technique which measures both reflection and transmission in a commercial RTP chamber with 8" wafer capability has been done at 3.3μm for the first time. Using fixed emissivity, good results are obtained for a heavily doped wafer but the pyrometer severely underestimates the temperature for a lightly doped wafer below 550°C. In the case of the lightly doped wafer, both reflectivity and transmissivity vary with temperature. This means the standard ripple detector system could not properly correct the data. By determining emissivity from both transmission and reflection data, accurate temperature measurement was achieved without *a priori* knowledge of the wafer doping density over the range of 400-700°C.

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