MRS Fall '89 A.10.8 DRAFT

TEMPERATURE MEASUREMENT BY INFRARED TRANSMISSION FOR RAPID THERMAL PROCESSING APPLICATIONS

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ABSTRACT

We report a new non-invasive optical technique for the measurement of the absolute temperature of silicon wafers in a rapid thermal processing environment. The method is based on the temperature dependence of the infrared absorption of silicon. Unlike pyrometry, the method can be used with a quartz processing chamber, and it is well-suited to the temperature range of 400 °C to 800 °C. Temperature resolution on the order of one degree can be achieved, and the method can easily be applied to homoepitaxial and certain heteroepitaxial growth cycles.

INTRODUCTION

The accurate measurement of the wafer temperature has long been an issue in the rapid thermal processing field. In most modern systems, temperature is measured by pryrometry, which looks at the quantity of emitted optical radiation in a certain wavelength window. Wavelengths around 3 µm are commonly used to measure temperatures in the 1000 °C range. At lower temperatures, however, pyrometry is subject to several systematic problems. First, under 700 °C, the emissivity of silicon is a relatively strong function of wavelength and temperature [1]. Second, at lower temperatures, it is desirable to use wavelengths on the order of 5 - 6 µm for accurate temperature measurement. However, for wavelengths longer than 3 µm, quartz is fairly opaque (fig. 1) [2]. Thus special windows on the processing chamber are required. This requirement is especially difficult if reactive gases and low pressures are used for rapid thermal growth processes such as Limited Reaction Processing [3].

It is well known of course that as the temperature increases, the bandgap of silicon decreases and the phonon population increases. Therefore, band-to-band optical absorption in silicon near the bandgap, which is an indirect process, will increase as temperature increases. Further, as temperature is increased, the increased intrinsic number of free carriers will lead to increased free carrrier absorption of any incident radiation. Both of these effects will lead to a strong temperature dependence of the optical absorption coefficient in silicon for a photon energy near the bandgap. Therefore, by monitoring infrared transmission near the band edge, one can measure the temperature of a silicon wafer. For reference points, the bandgap of silicon at ~410 °C is 0.96 eV (corresponding to a photon energy of 1.3 µm), and at 780 °C the bandgap is reduced to 0.81 eV (corresponding to 1.55 µm) [4].

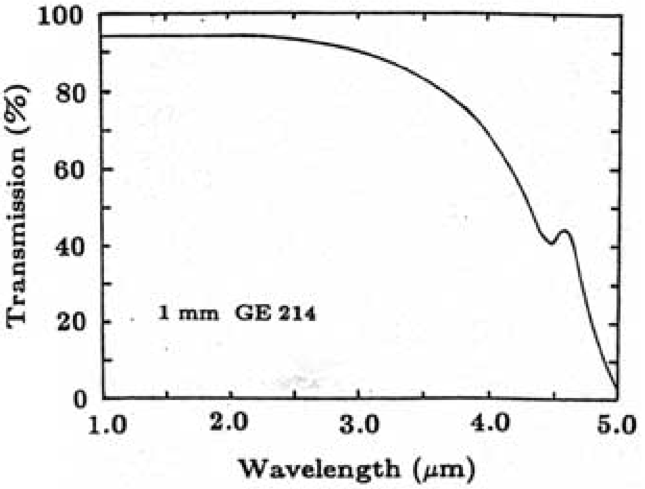

Fig. 1. Optical transmission of 1mm-thick quartz type GE 214 [2].

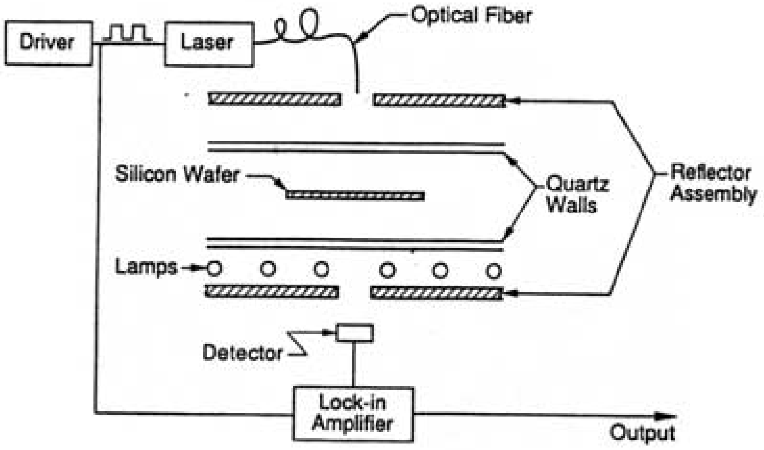

Fig. 2. Schematic diagram of the experimental rapid thermal processing system modified for optical transmission experiments.

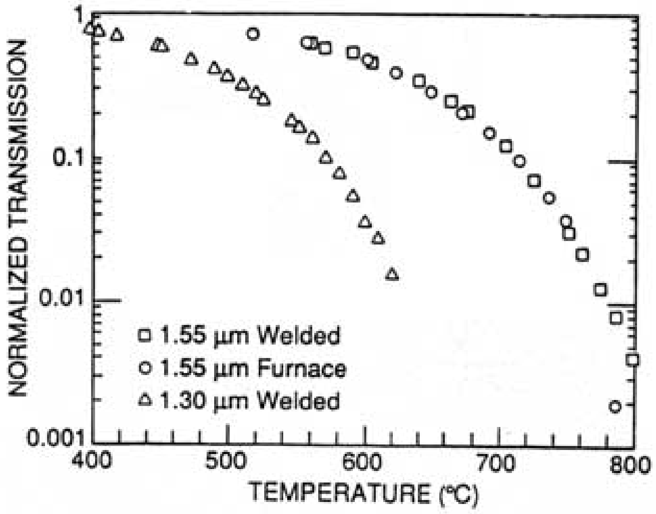

Fig. 3. Normalized transmission vs. temperature at 1.3 and 1.55 μm for a wafer thickness of 450 μm.

Therefore, one would expect these wavelength ranges to be useful over the 400 °C to 800 °C range. Fortunately, quartz is over 90% transparent (including surface reflections) near these wavelengths, making the method useful in a quartz-walled system.

EXPERIMENT AND RESULTS

A schematic diagram of our rapid thermal processing chamber (for epitaxial growth experiments) is shown in fig. 2. A semiconductor laser at 1.3 µm or 1.55 µm is electrically modulated and coupled into an optical fiber. The light from the fiber is then projected onto the wafer, and a detector is mounted beneath the lamp bank. A detector beneath the wafer outside the processing chamber detects the transmitted light, but also generates a large signal from stray light from the lamp bank. However the desired signal is easily separated from this background by the use of a lock-in amplifier. In addition to the absorption in the wafer, the light that reaches the detector depends on the laser power, optical alignment, geometrical factors, etc. To remove all of these dependences from the measurements, the transmission of every wafer is first measured at room temperature. For silicon wafers doped under 10^{17} cm^{-3}, there is negligible absorption ($\alpha < 1$ cm^{-1}) at room temperature [5,6]. The transmitted signal at elevated temperature is then always divided by the room temperature value to yield a normalized transmission t(T) which has no dependence on any factors such as laser power, alignment, etc.

To test the method, experiments were performed on a silicon wafer with a type "C" tungsten-rhenium thermocouple welded into the silicon to provide an intimate measure of the wafer temperature [7]. The wafer thickness was 450 µm and was lightly doped p-type (20-50 Ω-cm). The normalized infrared transmission t(T) was then measured as a function of the wafer temperature (as measured by the thermocouple). The results are presented in fig. 3 as triangles for 1.3 µm and squares for 1.55 µm. As expected, a decreased transmission at high temperature is noted, and the higher energy photons (1.3 µm) have higher absorption. Also plotted in fig. 3 is the normalized transmission at 1.55 µm of a another wafer of similar thickness measured in a modified conventional furnace, where the temperature was measured with a conventional thermocouple inserted into the furnace tube. Note the excellent agreeement between the two sets of data. The dominant source of error in this data is the error in the thermouple and meter. Based on manufacturers' specifications, the error in temperature is thought to be about one percent. With the data of fig. 3 as a reference, the optical transmission can then be used to monitor temperature on other wafers in subsequent cycles without thermocouples.

DISCUSSION

The light transmitted through the wafer is proportional to $R_1 \times R_2 \times e^{-\alpha(T)d}$, where R_1 and R_2 are the energy reflection coefficients at the top and bottom silicon surfaces, $\alpha(T)$ is the absorption coefficient at temperature T, and d is the silicon wafer thickness. Strictly speaking, one must also account for the possibility of interference resulting from multiple reflections inside the wafer. However, because of the divergence of the optical beam in our application, the rough back surface of the silicon wafer, and the decreased strenth of this contribution from extra surface reflections and extra path lengths through an absorbing media, multiple internal reflections can be ignored. The index of refraction of silicon over the wavelengths of interest exhibits only a very weak dependence on temperature. Using the data of Lukes [8], a change in R_1 or R_2 of only 2% from room temperature to 700 °C is expected. This small change is negligible compared to the reductions in transmission shown in fig. 4. Therefore, the entire change in t(T) can then be modeled by a simple $e^{-\alpha(T)d}$ relationship. The normalized transmission t(T) can be expresssed as

$$t(T) = e^{(\alpha(RT)-\alpha(T))d} \tag{1}$$

where $\alpha(RT)$ is the room temperature absorption coefficient. This may be inverted to give an expression for $\alpha(T)$,

$$\alpha(T) = \alpha(RT) - 1/d \times \ln(t(T))$$

Since the absorption coefficient for 1.3 and 1.55 µm at room temperature is << 1 cm^{-1}, the absorption coefficients at 1.3 and 1.5 µm of silicon at elevated temperature can be extracted from the data of fig 3. This data is plotted in fig. 4. To the best knowledge of the authors, this is the first time such data has been presented. The transmission of course depends on the wafer thickness. From (1), it is clear that the transmission for a wafer of thickness d, t(T,d), can be converted from one thickness to another by

$$t(T,d2) = t(T,d1)^{d2/d1}$$

Therefore a single calibration curve can be used for wafers of different thicknesses.

Of critical importance for practical application is the resolution of the technique. Clearly higher resolution is achieved when the transmission exhibits a strong relative change with temperature, which is seen in fig. 3 to occur when the transmission is low. For example, using the 1.55 µm signal near 700 °C, a 4% change in the lock-in amplifier output (easily detected) corresponds to a temperature change of only one degree. Thus it is advantageous to operate at a wavelength that gives the lowest transmission that can reliably be detected. To estimate the error caused by drift in a systematic variable such as laser power after the room temperature measurement, plotted in fig. 5 (a) is the 1.55 µm data of fig. 4, and curves representing what would be measured if there were such a +/- 25% systematic shift. Near 600 °C, this +/- 25% shift would cause a +/- 29 °C error in the extracted temperature, but near 775 °C, where the absorption changes more strongly with temperature, only a +/- 6 °C error would result. Based on our experience over many real runs, we have found it possible to keep all systematic variables fixed to within a few percent, corresponding to a temperature error on the order of only a degree. A similar analysis can be

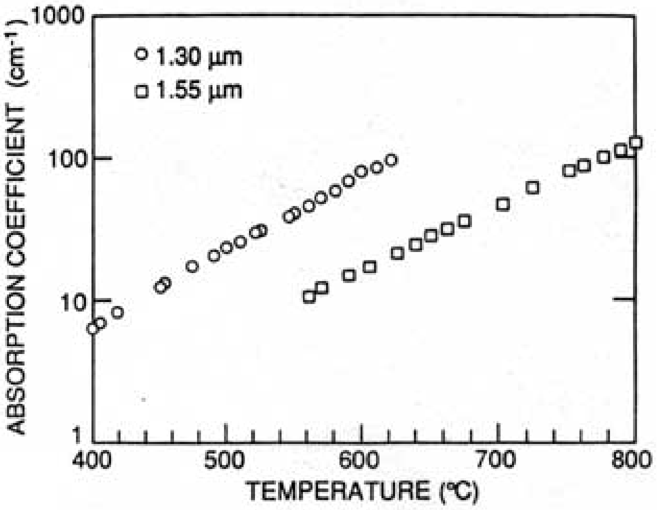

Fig. 4. Absorption coefficient of silicon at elevated temperature at 1.3 and 1.55 μm.

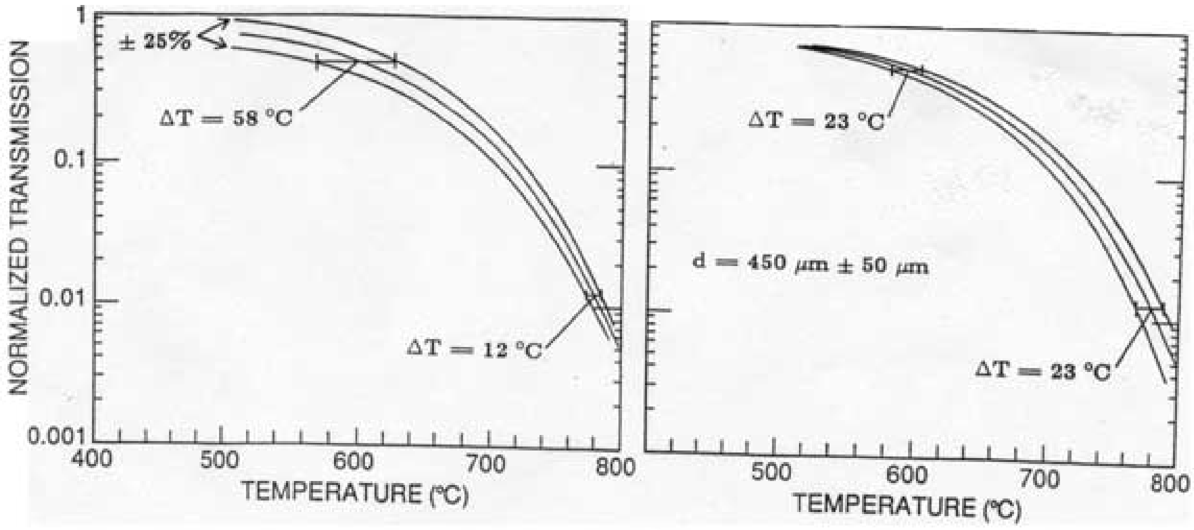

Fig. 5. Effect of (a) a +/- 25% change in laser power, and (b) the effect of a +/- 50 μm change in wafer thickness on normalized transmission and extracted temperature.

performed for errors in the wafer thickness (fig. 5(b)). An error in wafer thickness on the order of 5 µm would yield a 1 °C temperature error. Therefore the method can be used for epitaxial growth cycles. Indeed, we have used the method to control temperature during the growth of silicon and $Si_{1-x}Ge_x$ epitaxial layers in the 600-700 °C range. It should be stressed that once an accurate knowledge of silicon absorption vs temperature is established, no calibration for each individual system should be required, and the only parameter required is the thickness of the wafer.

SUMMARY

A new method for the measurement of the absolute temperature of silicon wafers based on infrared transmission has been proposed and demonstrated. The method has a practical resolution on the order of one degree, and can be used through thick quartz walls as might be used for low pressure deposition or growth experiments. Although the work was motivated by rapid thermal processing applications, the technology is very general and should lend itself to other applications.

ACKNOWLEDGEMENTS

The authors would like to thank K. Goel, P. Perrier, C. Reaves, and M. Nardin for assistnace with the optical fiber and laser technology, and J. Powell for prelimary caclulations. The support of ONR and NSF is greatly appreciated.

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