NON-INVASIVE SILICON TEMPERATURE MEASUREMENT BY INFRARED TRANSMISSION FOR RAPID THERMAL PROCESSING APPLICATIONS

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Abstract

We report the use of a new non-invasive optical technique to measure temperature in a rapid thermal processing environment. The technique relies on the increased optical absorption in the band-edge region (infrared) at elevated temperatures. The method is compatible with thick quartz walls on the processing chamber, and has approximately 1 °C resolution in the 500-800 °C temperature range. We have applied the technique to the growth of epitaxial silicon and silicon-germanium layers in this temperature range.

Introduction

The measurement of the wafer temperature in rapid thermal processing applications has long been a difficult and problematic issue. With the extension of rapid thermal processing into low-temperature silicon and silicon-germanium epitaxial growth [1], accurate in-situ temperature measurement becomes an even more critical issue. The growth rate and incorporated germanium fraction are stong functions of temperature in the 600-700 °C range. Conventional pyrometry approaches have a limited usefulness since the knowledge of the temperature to 1 °C accuracy requires a knowledge of the wafer emissivity to better than 0.01, and emissivity is a strong function of surface finish, field oxides, temperature, etc. [2,3]. Further, the 5 μm wavelength preferred in this temperature range (to avoid lamp interference) will not be transmitted through the quartz walls of the processing chamber.

Our approach relies on the decreased bandgap, higher phonon population, and increased free carrier concentrations in silicon at elevated temperatures. These effects cause increased optical absorption in the infrared (near band-edge) region due to both increased band-to-band and intraband absorption. By measuring the infrared optical transmission of the wafer in-situ during processing, one thus has an intimate measure of the wafer temperature.

Experiment and Results

A diagram of our rapid thermal processing apparatus for epitaxial growth is shown in fig. 1. It is essentially a Limited Reaction Processing reactor first described by Gibbons [4]. For this work, semiconductor lasers at 1.3 or 1.5 μm are modulated and coupled into a fiber which is projected onto the wafer. A lock-in amplifier is used to recover the transmitted signal and to avoid lamp interference. The quartz walls are over 90% transmissive in this wavelength range.

The detected signal of course depends on laser power, field oxides (effectively anti-reflection coatings), backside roughness, etc. Since all of these effects are temperature-independent, they are removed from the measurements by dividing the high temperature transmission of each wafer by the room temperature transmission of that wafer. Plots of normalized transmission vs. temperature are shown in fig. 2 for both a wafer in our apparatus (with the temperature measured for calibration purposes by a thermocouple welded to the wafer) and for a wafer in a modified conventional furnace. As can be seen, the agreement between the two calibration methods is good. The relative change in transmission is larger at higher temperatures, and at lower temperatures (larger bandgap) it is advantageous to use higher energy photons. For example, 1 °C resolution at 600 °C requires detecting a 0.8% relative change in the 1.5 μm transmission, but only a 4% change in the 1.3 μm signal. Extracted absorption coefficients at elevated temperature (not available in the literature) are shown in fig. 3.

The transmission of course depends on the wafer thickness, but correction of the results for the wafer thickness is straightforward using the $\exp(-\alpha d)$ relationship. (Due to the rough backside, the effect of multiple reflections through the wafer can be neglected). Even if the transmission is not corrected for a change in wafer thickness, a +/- 50 μm change in a 450 μm wafer gives a temperature error of about +/- 12°C (fig. 4). A more realistic +/- 5 μm gives an error of only 1 °C. Therefore the method can be applied to epitaxial growth without correcting for the change in the wafer thickness. The effect of fluctuations in laser power, etc., is simulated in fig. 5. Near 700 °C, a 25% change in laser power causes a temperature error of 10 °C. A stability of a few % (easily done) is required for 1 °C accuracy.

We have applied this method to the control of temperature during the epitaxial growth of silicon and silicon-germanium in the 600-700 °C range. Accurate temperature control is critical since the growth rate and incorporated germanium fraction are strong functions of temperature [5] (fig. 6). Fortunately, thin SiGe layers on the order of those used for HBT's have negligible effect on the transmission (fig. 7). SIMS germanium profiles of samples grown without temperature feedback (open-loop) and with this transmission feedback control are shown in fig. 8. Note the improved control over the layer composition.

Summary

A method for the non-invasive measurement of silicon wafer temperature based on infrared transmission has been presented. The method is well-suited to the 400-800 °C temperature range, can be used through thick quartz walls, and is compatible with rapid thermal processing and epitaxial growth. Improved control of silicon-germanium film growth has been demonstrated. This work was supported by ONR and NSF.

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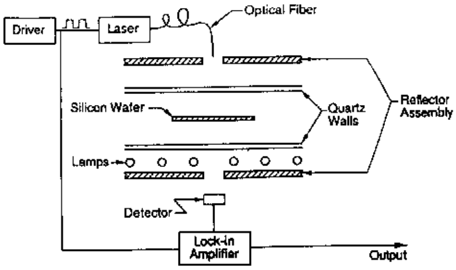

Fig. 1. Schematic diagram of the experimental rapid thermal processing system modified for optical transmission experiments.

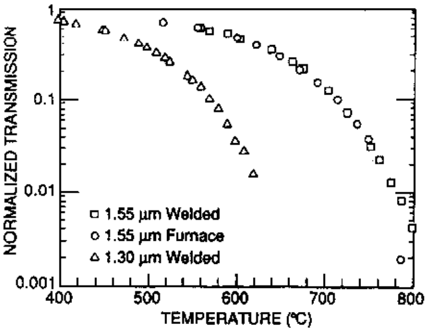

Fig. 2. Normalized transmission vs. temperature at 1.3 µm and 1.55 µm for a wafer thickness of 450 µm.

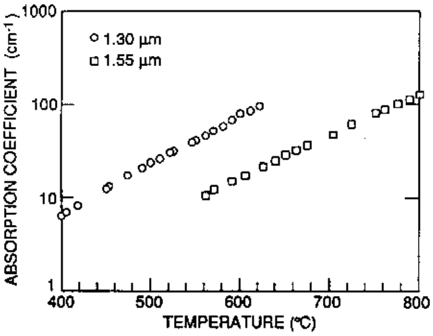

Fig. 3. Absorption coefficient of silicon at elevated temperature at 1.3 µm and 1.55 µm.

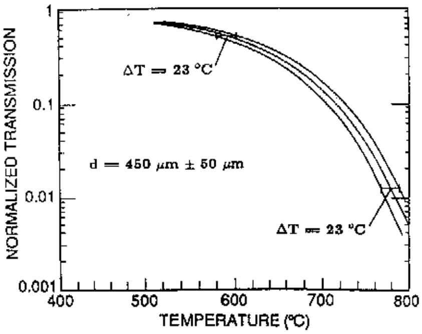

Fig. 4. Effect of a +/- 50 µm change in wafer thickness on normalized transmission and extracted temperature.

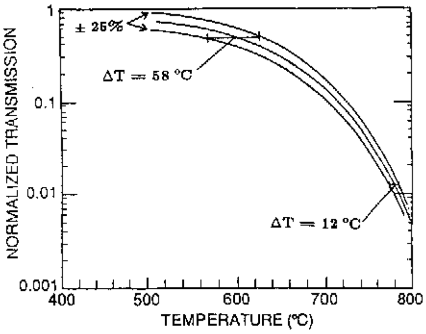

Fig. 5. Effect of a +/- 25% change in laser power on transmission and extracted temperature.

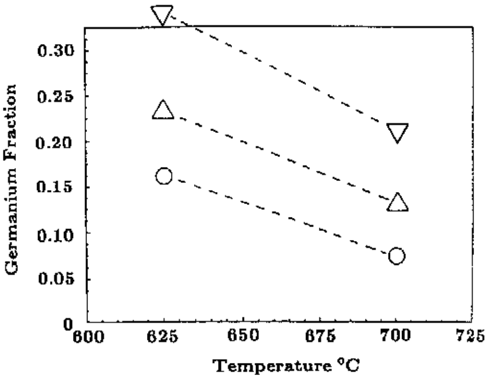

Fig. 6. Dependence of germanium content (mole fraction) in silicon-germanium films on temperature for three different gas flows.

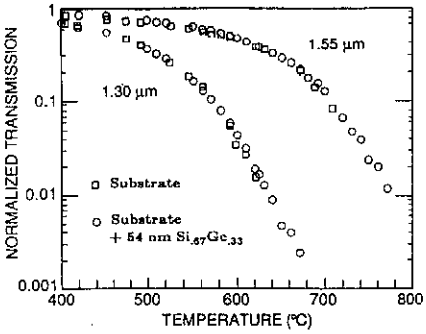

Fig. 7. Normalized transmission before and after growth of 54 nm of $Si_{0.67}Ge_{0.33}$ on both sides of a silicon substrate.

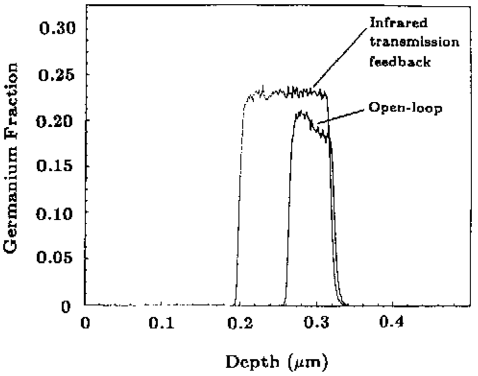

Fig. 8. SIMS profiles of SiGe layers grown at a nominal temperature of 625 °C with and without temperature feedback by optical transmission.