

Silicon temperature measurement by infrared transmission for rapid thermal processing applications

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The use of optical transmission at 1.3 and 1.55 μm is reported to measure the temperature of silicon wafers in a rapid thermal processing environment. Physically, as the wafer temperature increases, infrared transmission drops due to band-gap reduction and an increased phonon population. This method has been used to measure wafer temperature with a resolution of several degrees from 400 to 800 $^{\circ}\text{C}$, and is compatible with the thick quartz walls of the processing chamber. As part of this work, the absorption constant of silicon at 1.3 and 1.55 μm from 400 to 800 $^{\circ}\text{C}$ has also been measured.

The measurement of silicon wafer temperature is, of course, critical for the control of any thermally dependent process. In this letter we report the use of a new technique to measure wafer temperature over the range of room temperature to 800 $^{\circ}\text{C}$. The method relies on the temperature dependence of infrared transmission, and is well suited to rapid thermal processing applications.

In "equilibrium" environments, where the wafer is surrounded by materials which are the same temperature as the wafer itself (such as a furnace), one can reliably use thermocouples to deduce wafer temperature. In nonequilibrium environments, where the wafer "sees" surroundings of a different temperature, temperature measurements are a problematic issue. In such environments, one frequently uses pyrometry to measure wafer temperature. The pyrometry technique has at least two practical limitations, however. First, absolute knowledge of temperature depends on the emissivity of the monitored wavelength, and silicon emissivity is known to be a strong function of temperature, wavelength, and surface finish, especially in the range under 600 $^{\circ}\text{C}$.¹ Furthermore, at temperatures under 800 $^{\circ}\text{C}$, it is common to use pyrometers which operate at long wavelengths (e.g., 5 μm), and special windows on the processing chamber are required. (Quartz transmission typically drops off at 2–3 μm .) Furthermore, in rapid thermal processing applications, one must be careful to shield the light from the lamp banks used for heating from the pyrometer.

Optical absorption in silicon at photon energies near that of the band gap proceeds by an indirect process of photon absorption coupled with multiple phonon absorption or emission. As temperature increases, the phonon population of course increases and the band gap decreases,² which in turn give rise to a corresponding decrease in infrared transmission near the band edge. Therefore, one can use infrared transmission as a monitor of wafer temperature. For reference points, the band gap of silicon at room temperature is 1.12 eV. At ~ 410 $^{\circ}\text{C}$ the band gap is reduced to 0.96 eV, corresponding to the photon energy of 1.3 μm radiation, and at 780 $^{\circ}\text{C}$ the band gap is reduced to 0.81 eV, corresponding to the photon energy of 1.55 μm .² Therefore, one would expect these wavelength ranges to be especially useful for tem-

peratures up to about 800 $^{\circ}\text{C}$. Fortunately, quartz is over 90% transparent at these wavelengths, making the method useful in a quartz-walled system.

A schematic diagram of our experimental rapid thermal processing system is shown in Fig. 1. A semiconductor laser at 1.3 or 1.55 μm is electrically modulated and coupled into an optical fiber. The light from the fiber is then projected onto the silicon sample, and an optical detector is mounted beneath the lamps and reflector assembly. A lock-in amplifier is used to separate the desired signal from the lamp interference. Because the detected optical signal depends on laser power, alignment of the detector, etc., the transmission of all samples is first measured at room temperature. Signals at high temperature are divided by this cold value to remove dependence on such systematic variables.

Normalized transmission data for a lightly doped *p*-type (~ 10 –50 $\Omega\text{ cm}$) silicon wafer of 450 μm thickness are shown in Fig. 2. Open squares (1.55 μm) and triangles (1.3 μm) refer to data taken in the system of Fig. 1. The absolute temperature was measured by a tungsten-rhenium thermocouple (type "C") which was welded into the middle of the semiconductor wafer, providing an intimate measure of wafer temperature.³ The open circles (1.55 μm) represent data measured in a conventional furnace tube (adapted for transmission measurements) where temperature is measured by a thermocouple separate from the test wafers. As can be seen, the two sets of data points at 1.55 μm correspond to within a few degrees. As expected, the higher energy photons (1.3 μm) have a much lower transmission than the 1.55 μm photons. Furthermore, the relative transmission decreases faster as the temperature increases, presumably as the band gap drops below the photon energy. To use transmission to accurately monitor temperature, a strong relative dependence on temperature is desired. For example, at 750 $^{\circ}\text{C}$, a 3% relative change in transmission at 1.55 μm (easily detected by simple electronics) corresponds to only a one degree change in temperature. Similar resolution is obtained at 600 $^{\circ}\text{C}$ with 1.3 μm light. In addition to absorption, the transmission will also depend on the reflection at the silicon surfaces. Extrapolating the temperature dependence of refractive index at 1.4 μm from 500 to 700 $^{\circ}\text{C}$ ⁴ and using simple calculations, the

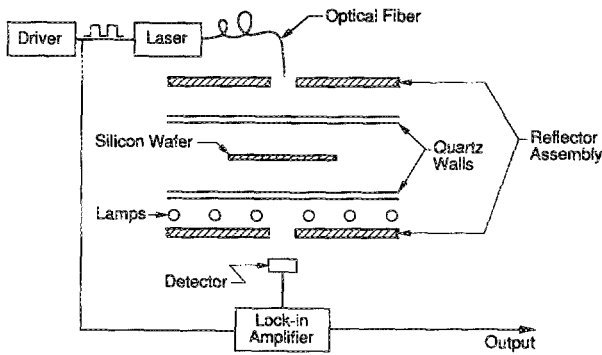


FIG. 1. Schematic diagram of the rapid thermal processing system adapted for infrared transmission measurements.

transmitted power at an air-silicon interface is expected to change by less than 2% from room temperature to 700 °C. Thus nearly all change in transmission at elevated temperature results from a change in absorption.

Because of the rough back surface of a silicon wafer, and absorption from the extra path length, negligible light collected by the detector is thought to undergo multiple reflections inside the wafer. Therefore, the temperature dependence of transmission through the wafer can be modeled by a simple $e^{-\alpha d}$ relationship, where α is the absorption coefficient and d is the wafer thickness. From the data in Fig. 2, one can then easily extract the change in absorption coefficient at 1.3 and 1.55 μm from room temperature:

$$\alpha(T) - \alpha_{RT} = -(1/d) \ln[t(T)]. \quad (1)$$

$\alpha(T)$ and α_{RT} are absorption constants at elevated temperature and room temperature, respectively, and $t(T)$ is the transmission at temperature T divided by the room-temperature transmission. Since the room-temperature absorption in this wavelength range is $\ll 1 \text{ cm}^{-1}$,⁵ the expression in (1) reduces to $\alpha(T)$, which is plotted in Fig. 3. To the best of our knowledge, this is the first time absorption data for silicon at these wavelengths for this temperature range have been reported. The dominant source of error in these data (and in Fig. 2) is thought to be the absolute measurement of the temperature, the error of which is estimated to be less

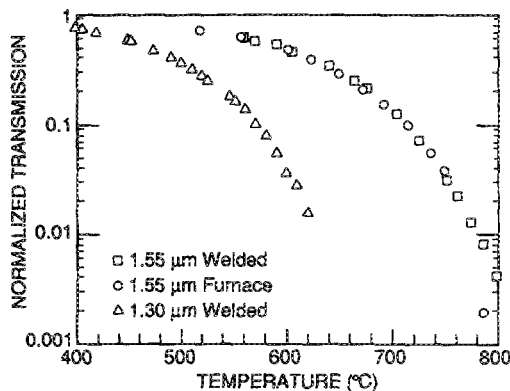


FIG. 2. Optical transmission divided by room-temperature transmission at 1.3 and 1.55 μm at elevated temperature.

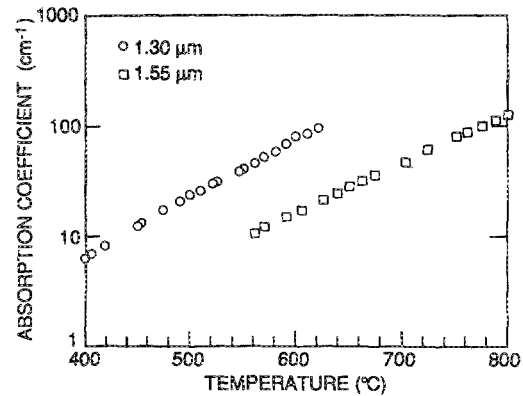


FIG. 3. Silicon optical absorption coefficient $\alpha(T)$ at 1.3 and 1.55 μm at elevated temperature.

than 1% based on thermocouple and meter specifications. Therefore, although the resolution and repeatability of the technique are $\sim 1^\circ\text{C}$, the absolute accuracy is at present $\sim 7^\circ\text{C}$ and is limited by the accuracy of the temperature measurement during calibration. Experiments are in progress to determine the temperature with greater accuracy during the measurement of the absorption constants.

The transmitted signal of course depends on the wafer thickness, but one can easily correct for different wafer thicknesses using the $e^{-\alpha d}$ relationship. Once the wafer thickness is known, this method provides for an absolute measurement of wafer temperature, and should not suffer from any systematic errors as can occur in pyrometry. Simple calculations show that a 5 μm change in the thickness of a 500 μm wafer will produce an error in temperature (if not corrected for thickness) on the order of one degree over the range of practical interest. Therefore, the method is also well suited for the measurement of temperature during epitaxial growth cycles during which the wafer thickness could change by a few microns.

Furthermore, the presence of thick dielectric layers on the surface (such as field oxides), which can affect emissivity and thus pyrometers,⁶ should not affect this technique. Any interference effects on transmission should be fairly independent of temperature and can be normalized out by dividing by the room-temperature transmission.

In 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 quartz windows. The absolute accuracy of the method is at present limited to $\sim 7^\circ\text{C}$, but more accurate knowledge of absorption constants at elevated temperature will reduce this error. Although this work was motivated by rapid thermal processing applications, the technology is very general and should lend itself well to other applications. Optical absorption data for silicon at 1.3 and 1.55 μm at elevated temperatures have also been reported.

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