Noncontacting acoustics-based temperature measurement techniques in rapid thermal processing

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ABSTRACT

Temperature measurement of silicon wafers based on the temperature dependence of acoustic waves is studied. The change in the temperature-dependent dispersion relations of the plate modes through the wafer can be exploited to provide a viable temperature monitoring scheme with advantages over both thermocouples and pyrometers. Velocity measurements of acoustic waves through a thin layer of ambient directly above the wafer provides the temperature of the wafer-ambient interface.

1. INTRODUCTION

Most of the semiconductor processes are at least partially thermally driven and, hence, one of the most important parameters that needs to be accurately monitored and controlled is temperature. There are, however, currently no effective means of monitoring wafer temperature in-situ. While a thermocouple provides a fairly precise measurement, it generally must contact the wafer, acting as a heat sink and creating a temperature nonuniformity. It can also react with the wafer at higher temperatures, contaminating it, and is incompatible with the harsh processing conditions (reactive gases and high temperatures) present in the processing chambers. Optical pyrometers are noncontacting, but are inaccurate. Because the temperature measurement is based on the thermal radiation of the wafer, it is strongly affected by the emissivity of the wafer surface which changes drastically with film growth or depositions. Care must also be taken to ensure that the heat source does not have a significant amplitude in the optical frequency to which the pyrometer is sensitive.

While a great deal of research has been performed on trying to improve the current temperature measurement technology, most efforts have been spent on overcoming the limitations of existing technology. An approach to obtaining an effective temperature measurement based on an entirely different physical phenomenon is presented. Acoustic waves in the silicon wafer, as well as the ambient directly above it, are affected in a systematic way by temperature, and this is exploited to obtain a reliable temperature measurement. One scheme explored in this work, based on the temperature dependence of acoustic waves, can deliver temperature measurements of the wafer, and the gaseous environment above it, with sensitivities to better than $\pm 1°C$ with sampling frequencies of up to a few thousand per second.

2. TEMPERATURE MEASUREMENT OF WAFER BULK

The elastic constants of silicon are functions of temperature. Thus, the propagation characteristics of all the modes of acoustic waves in the silicon will be affected in a systematic way by the temperature. Upon theoretical studies of the different modes, the fundamental plate mode (zeroth-order antisymmetric mode Lamb wave) have been found to provide the greatest sensitivity, and will thus be used exclusively in obtaining temperature data. The temperature dependence of the phase and group velocities as a function of frequency at 0°C is shown in Fig. 1. This dependence is to the first order constant throughout the temperature range of interest (0°C-1200°C).

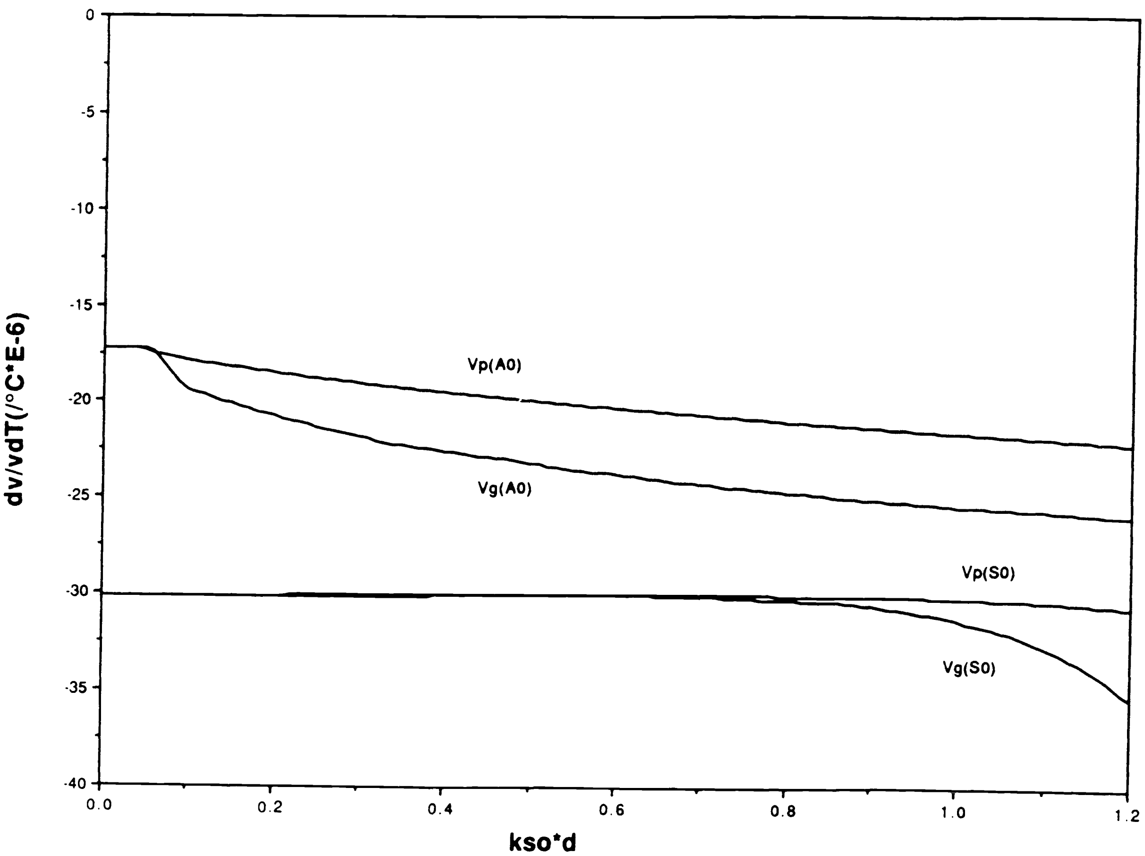

Fig. 1. Temperature dependence of plate mode phase and group velocities.

Using this velocity dependence on temperature, it is possible to extract the temperature information from generating and detecting fundamental plate-mode acoustic waves in the silicon wafer. This is done using the set-up shown in Fig. 2. A nitrogen laser, with a pulse width of 800 ns and pulse energy of 2.5 mJ is weakly focused onto a silicon wafer with an excitation area of 1 mm x 5 mm . At a point 2-4 cm

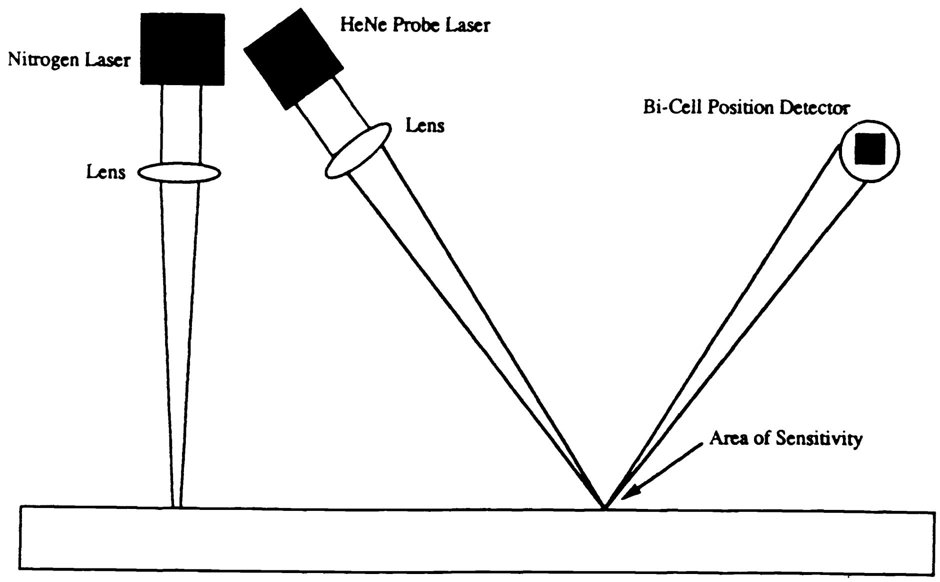

Fig. 2. Excitation and detection of acoustic waves.

away, an expanded He-Ne beam is tightly focused onto a spot on the silicon surface and the reflected beam is projected onto a bicell detector. The pulsed nitrogen laser produces a mechanical strain due to the localized thermal expansion caused by the laser-induced heating. The initial mechanical strain produces a wide range of acoustic modes in the wafer, among which is the fundamental plate mode in which we are interested.

By measuring the time-of flight of the highest frequency components of the waveform which arrive earliest, information on the bulk temperature can be obtained. Digitization of the waveform to obtain the time delay of the longer wavelength components will yield a higher resolution. Because the plate mode is supported by the entire bulk of the wafer, the temperature obtained by the system yields an integrated average of the bulk of the wafer in the path of the wave between the excitation and detection points. Surface conditions do not affect the propagation characteristics of the plate modes as long as their depths are small compared to the thickness of the wafer (approximately 500 μm). By scanning the laser beams across the surface, a temperature mapping of the wafer can be obtained.

3. TEMPERATURE MEASUREMENT OF LAYER OF AMBIENT DIRECTLY ABOVE THE WAFER

The set-up used for the excitation and detection of acoustic waves in the wafer can also be used for the excitation and detection of waves through the layer of ambient directly above the wafer. Unlike the detection of the plate modes through the solid, where the changes in the gradient on the wafer were observed, the changes in the index of refraction in the ambient caused by the compression and rarefaction of the gas as the acoustic pulse propagates is measured. Areas of the laser probe where the diameter of the beam is larger than the acoustic wavelength do not contribute to the detected signal. Only the region of the beam near the focus (i.e., the region directly above the wafer) is affected by the acoustic pulse. Thus, the detector is only sensitive to acoustic waves directly above the wafer.

Although the use of the nitrogen laser as the source of the acoustic pulse in the ambient is convenient when this system is used in conjunction with the measurement using the plate modes in the silicon, a scheme without the nitrogen laser is more viable if the temperature measurement of the ambient is to be performed alone. In place of the nitrogen laser, an acoustic air transducer is used (Fig. 3). A transducer designed to provide a 100 kHz signal is placed perpendicular to the plane of the wafer. An acoustic wave launched parallel to the wafer surface is detected at two points using two probe-beam deflection detectors. By measuring the phase difference between the signals detected at the two points, the velocity of the acoustic wave can be accurately determined.

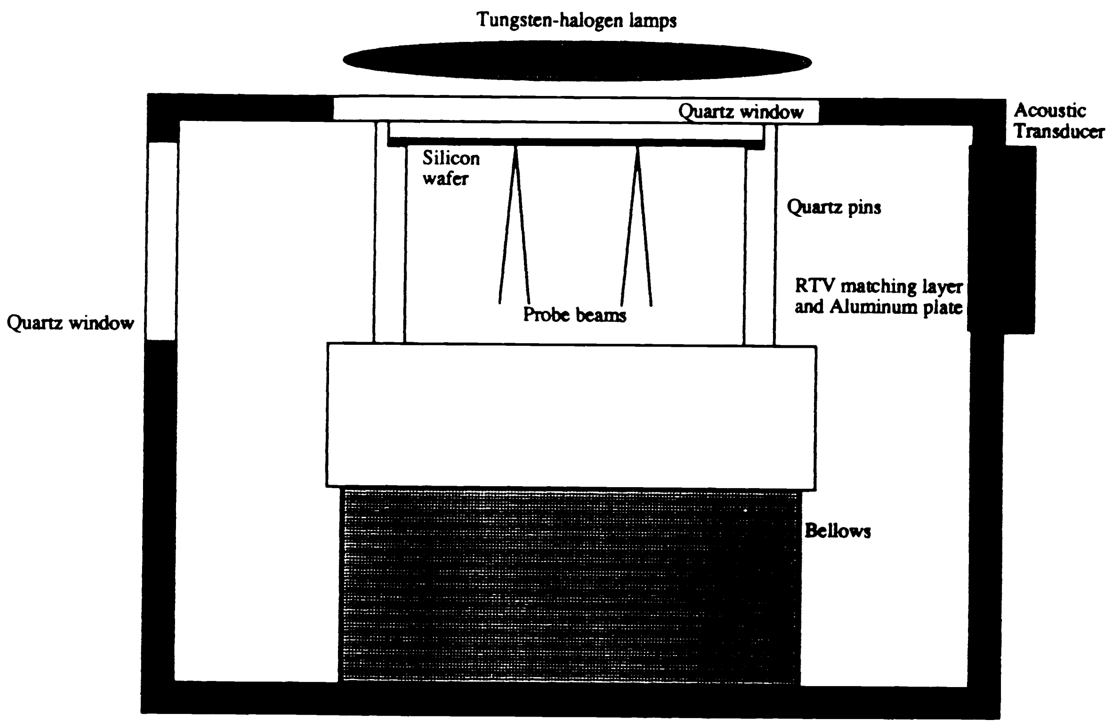

Fig. 3. Set-up for the temperature measurement of the layer of ambient directly above the silicon wafer.

The acoustic wave propagation in gases is to the first order nondispersive, and independent of pressure. From thermodynamic considerations, the velocity is computed to be $v = K\sqrt{T}$ where K is a constant characteristic of the gas mixture. Such a strong temperature dependence of the velocity can be exploited to obtain temperature measurements to better than $\pm 1°C$ with relative ease. Figure 4 shows preliminary results of the velocity measurements as a function of temperature as detected using a thermocouple welded

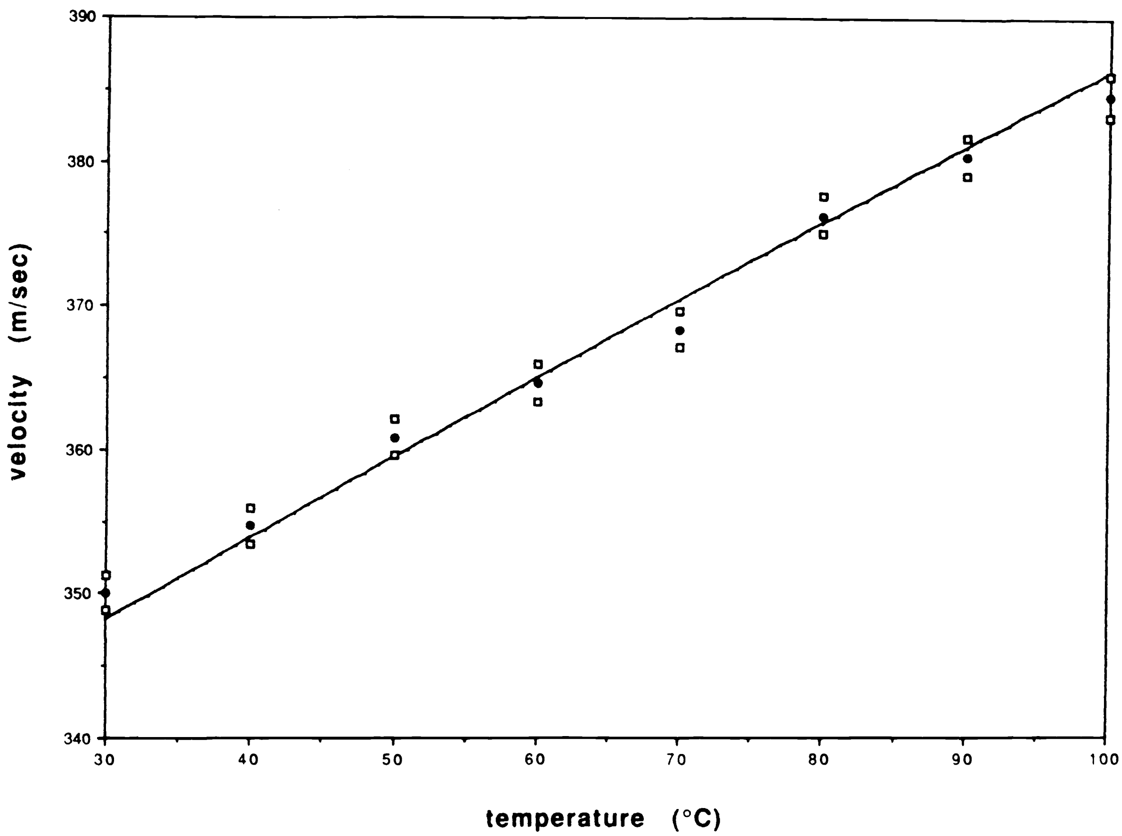

Fig. 4. Acoustic wave velocity in air as function of temperature.

onto the silicon wafer. Close correlation of the theoretical velocity computed from thermodynamic considerations and the experimental velocity charted against wafer-substrate temperature as measured by a thermocouple welded onto the wafer suggests that there is a very close correlation between the wafer bulk temperature and the temperature of the ambient directly above the wafer. Thus, while the system will yield the temperature of the layer of ambient directly, it can also be used to indirectly measure the wafer bulk temperature.

The system, however, has the disadvantage over the temperature measurement via the plate mode waves in that the attenuation of the acoustic waves in gases is inversely related to pressure. For applications such as oxidation, diffusion, crystal growth, annealing, higher-pressure CVD, and other processes typically carried out at higher pressures, the temperature measurement via acoustic waves in the ambient is ideal. For applications requiring much lower pressures, such as metallization, LPCVD, low pressure plasma, and RIE processes, and others, the temperature measurement via plate mode acoustic waves can be used.

4. MEASUREMENTS IN A RAPID THERMAL PROCESSOR

The ambient temperature measurement scheme has been installed into a rapid thermal processor designed by Texas Instruments. An array of acoustic transducers are bonded onto a quarter-wave plate of aluminum for mechanical support, a quarter-wave plate of RTV for impedance matching, and a 1 0 mil aluminum sheet to prevent the outgassing of the RTV in the vacuum chamber. The transducer is installed onto a port at the same level as the top heating window of the chamber. The silicon wafer, held up by three notched quartz pins, is raised to the level of the transducer, about 100 μm below the top window. The separation of the wafer from the window is determined by the depth of the notch on the quartz pins. The small separation minimizes convection currents which interfere with acoustic wave detection. The two laser beams are brought into the chamber through optical windows on the side of the chamber. Operation of the sensor in 3 torr of nitrogen ambient has been achieved. Further acoustic matching techniques should bring the operation of the sensor in the hundred millitorr regime.

5. CONCLUSION

An entirely different method of temperature measurement, based on the temperature dependence of acoustic waves, has been studied. The change in the dispersion relations of the plate modes through the wafer as a function of temperature can be exploited to provide a viable temperature monitoring scheme with advantages over both thermocouples and pyrometers. Temperature measurement based on the velocity dependence of acoustic waves through a thin layer of ambient directly above the wafer provides a measurement which has been previously unavailable. Temperature monitoring of the thin layer of ambient directly above the silicon wafer will be important in better controlling processes where the mass transport mechanisms and the effects of stagnant layers play a significant part in the process. The information about the temperature of the layer of ambient can also be used to obtain the wafer bulk temperature. Because of high temperature sensitivity of the acoustic wave velocity in gases, this system will provide a practical in-situ temperature measurement scheme with sensitivities better than $\pm 1°C$.

6. ACKNOWLEDGEMENTS

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