

IN-SITU ULTRASONIC THERMOMETRY OF SEMICONDUCTOR WAFERS

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ABSTRACT

We report a temperature measurement technique based on the temperature dependence of acoustic wave velocity in silicon wafers. The zeroth order antisymmetric Lamb wave is excited in the wafer using the quartz pins which support the wafer during processing. Extensional waves are generated in the quartz pin by a PZT-5H transducer and the acoustic energy is coupled to the Lamb wave at the contact between the sharpened end of the pin and the wafer surface. The detection is done by a similarly modified quartz pin. By measuring the time of flight of the Lamb wave in the wafer between the two pins, we have monitored the wafer temperature in-situ in the 20 - 1000°C range with ± 1 accuracy. With 8 spring loaded pins placed on a circular array around the wafer, 28 different measurements are made giving information about different regions. Using tomographic reconstruction techniques, spatial temperature distribution with 2 cm pixel size is then calculated. Excellent agreement is observed between the readings of thermocouples attached to the wafer, and calculated values for ultrasonic tomography.

INTRODUCTION

Temperature is a very critical parameter to be accurately monitored and controlled in semiconductor processing, since most processing steps are thermally activated [1]. Currently, optical pyrometers are the dominant temperature sensors in semiconductor industry. Their reading depends on the thermal radiation from the wafer which is very sensitive to wafer emissivity variations. Various factors such as film deposition, surface roughness and doping levels affect emissivity, making pyrometer readings inaccurate. Thermocouples are accurate to $\pm 5^\circ\text{C}$, but they are not used in-situ, because of contamination at high temperatures and non uniformity problems. Thermal expansion measurements suffer from low sensitivity [2].

Acoustic waves are also sensitive to temperature, through the temperature dependence of elastic constants. For silicon, these sensitivity figures have been measured [3]. Using these figures we have calculated that, for antisymmetric Lamb waves, the group velocity has a temperature coefficient of $-1.6 \times 10^{-5} (1^\circ\text{C})$, which is an order of magnitude larger than the thermal expansion coefficient.

For in-situ ultrasonic thermometry, we use the quartz support pins placed near the edge of the wafer to excite ultrasonic waves in the wafer. In particular, the zeroth order antisymmetric Lamb wave (A0 mode) is excited and the time of flight information is used to measure the wafer

temperature. In the frequency range used, the wavelength is around 0.5 cm, making the technique virtually insensitive to other process parameters such as surface roughness. It is also non contacting in that there is no additional contact to the wafer other than the quartz support pins. Using ultrasonic thermometry, wafer temperature is monitored in-situ, in the 20 - 1000°C range with $\pm 1^\circ\text{C}$ accuracy. By increasing the number of transducer pins to 8, 28 measurements from different regions of the wafer are made, and the temperature distribution across the wafer is calculated, in-situ, using tomographic techniques.

PIN TO PIN TIME OF FLIGHT MEASUREMENT

In single wafer semiconductor processing chambers, the wafers are supported by quartz pins as depicted in Fig. 1. The low thermal conductivity of quartz prevents heat transfer from the wafer to the environment and maintains temperature uniformity in the wafer. These pins are used to couple acoustic energy to a Lamb wave mode in the wafer. The PZT-5H transducer bonded to the end of the quartz rod generates extensional waves with 40% fractional bandwidth around 200 KHz. The transducers are isolated from the high temperature and reactive gases in the process chamber by placing them in a nitrogen cooled, stainless steel housing. To have a well defined, repeatable point contact with the wafer, the contacting end of the quartz rod is sharpened and the tip is rounded to a radius of 100 μm .

Extensional waves are generated in the quartz rod by applying a 130 V negative electrical pulse at the PZT transducer terminals. This mode is coupled to the A0 mode in the wafer at the Hertzian contact formed at the quartz pin wafer interface. The Lamb wave propagates across the wafer. In a reverse process, an electrical signal is detected at the receiving transducer.

The time of flight data is obtained by measuring the time delay between a zero crossing in the echo signal reflected from the tip of the transmit transducer and the received signal at the other transducer. By using the zero crossing at the echo signal, the effect of temperature in the quartz pins is eliminated assuming that they are identical. In Fig. 2, the variation of pin to pin time of flight is plotted against the wafer temperature measured by a C-type thermocouple welded to the wafer. The sample is a 0.5 mm thick (100) silicon wafer with 10 cm diameter and the measurement is done in $\langle 100 \rangle$ direction. The wafer is heated by a 500 W tungsten halogen lamp. The time of flight is a very linear function of temperature and for this configuration, the sensitivity is 1.23 nsec/ $^\circ\text{C}$. The repetition rate is limited by the acoustic ringing in the wafer to 20 Hz, which is more than sufficient for temperature control applications.

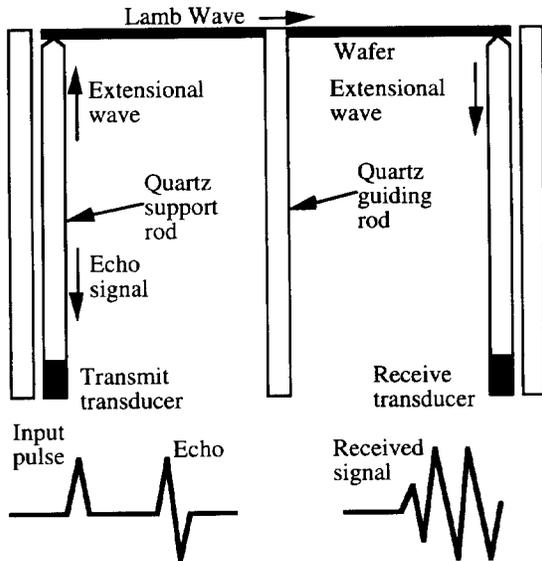


Figure 1. Pin to pin time of flight measurement setup.

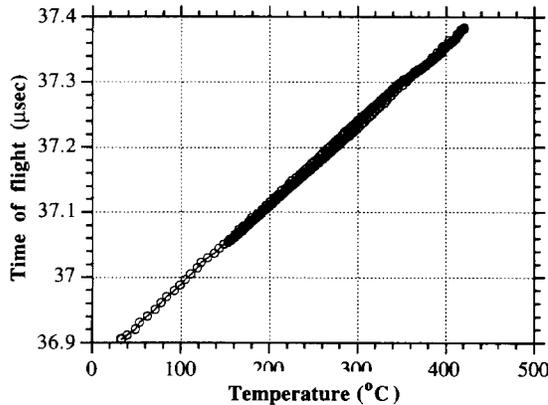


Figure 2. Measured time of flight as a function of wafer temperature.

The accuracy of temperature measurement depends on the signal to noise ratio of the system. At constant temperature, the system is calibrated and the variation of temperature computed from the time of flight measurement is monitored as a function of signal to noise ratio. Fig. 3 shows the results of this experiment. By spring loading the pins, a larger Hertzian contact is made, and the system has a signal to noise ratio exceeding 50 dBs, which corresponds to a relative accuracy of better than $\pm 1^\circ\text{C}$.

Ultrasonic thermometry is then used to measure wafer temperature in an actual semiconductor processor. The transducer pins and the housing are integrated in a Texas Instruments rapid thermal processor. To monitor temperature in-situ, during processing, a calibration run is made taking the thermocouple reading as reference at steady state levels. The data is then used to obtain a third order polynomial fit to relate time of flight to temperature. Fig. 4 shows the data obtained during an actual temperature transient in the rapid thermal processor. The thermocouple and ultrasonic thermometer results agree very well in the whole temperature range from room temperature up to 1000°C . The difference in the cooling interval results from

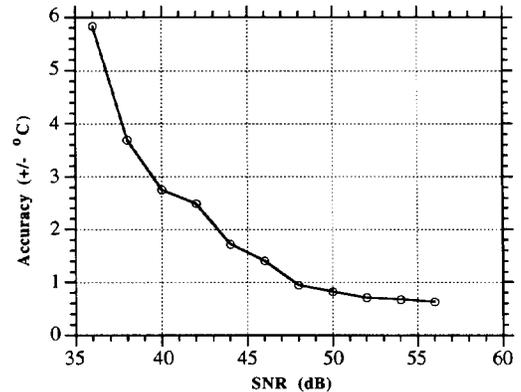


Figure 3. Relative temperature measurement accuracy of ultrasonic thermometry system as a function of SNR.

the fact that the thermocouple reads the temperature at the center whereas the ultrasonic sensor gives the average wafer temperature. The heat loss is larger near the edge of the wafer resulting a smaller average temperature than the center.

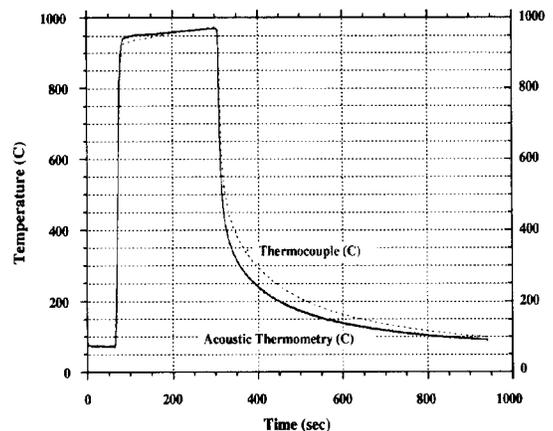


Figure 4. Actual temperature transient in rapid thermal processor measured by ultrasonic thermometer and thermocouple.

TEMPERATURE TOMOGRAPHY

The pin to pin time of flight measurement provides the average wafer temperature along the path connecting the two quartz pins. Of more importance is the temperature distribution on the wafer for temperature and process control applications. This information can be collected by measuring average temperature along many paths and inverting the data to get spatial distribution. Ultrasonic thermometry is used for this purpose and wafer temperature distribution is obtained by tomographic reconstruction.

Eight quartz pins are placed around the periphery of the silicon wafer as shown in Fig. 5. The pins are spring loaded to have repeatable contact with the wafer and better signal to noise ratio. With 8 pins, average temperature

measurements along 28 different paths can be made as depicted in the same figure. The measurement procedure is the same as the two pin configuration. Using a computer controlled circuitry, the transducers are excited sequentially and time of flight data is collected from the other pins. Since all data acquisition is done sequentially, the data rate for an image is 1.4 sec. This figure can be reduced to 0.4 sec by using multiple time interval counters. For calibration, the wafer is brought to certain temperatures at steady state and the data for each path is stored. The acoustic anisotropy of silicon is eliminated by this calibration.

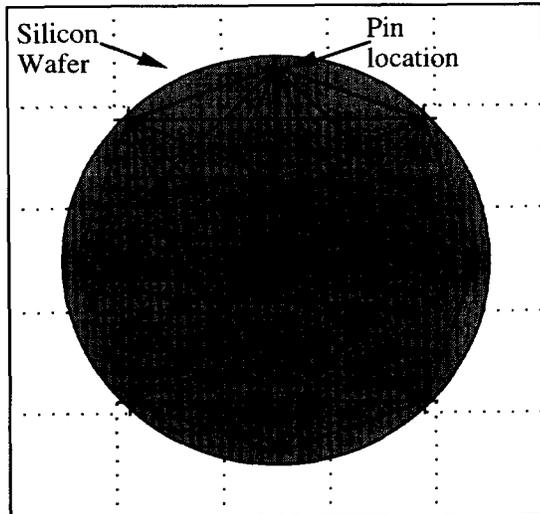


Figure 5. The pin locations and reference thermocouple joints used in temperature tomography. A possible rectangular pixel map is shown by the dashed lines.

For tomographic reconstruction the linear equation solving approach is used [4]. Two pixel maps are considered and corresponding projection matrices are calculated. To form the images, the time of flight data is converted to average temperature using the calibration function and the pixel values are calculated by a matrix multiplication. Since the maximum number of pixels is 28 the computation time is negligibly small as compared to data acquisition. Fig. 6 shows the reconstructed temperature distribution by ultrasonic thermometry along with the thermocouple reference values using circular pixels. This pixel map is convenient for semiconductor processors using circular heating lamp structure [5]. The circularly symmetric temperature distribution is obtained by masking the heating lamp properly. The agreement between the thermocouple readings and the acoustic tomography is excellent except the outermost ring, where the temperature gradient is large. Non symmetrical temperature profiles can be calculated with 2 cm pixel size by using a pixel map as in Fig. 5, by changing the projection matrix.

The resolution and accuracy of the temperature tomography system can be improved by increasing the number of measurement paths. Also, a priori information obtained from wafer heating simulations can be incorporated in reconstruction to minimize measurement errors.

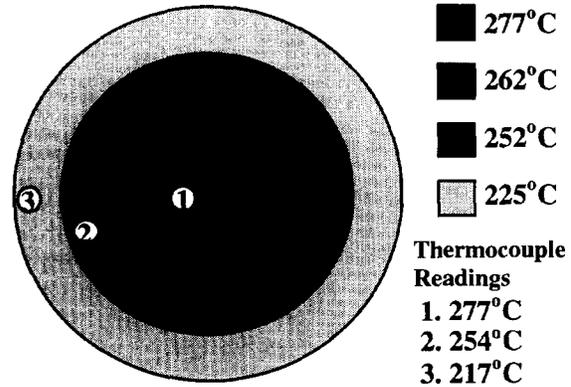


Figure 6. Calculated ultrasonic temperature tomography image of the silicon wafer with circular pixel map.

CONCLUSION

Ultrasonic thermometry is used to measure in-situ wafer temperature in semiconductor processing. The method is capable of measuring average wafer temperature in 20-1000°C range with $\pm 1^\circ\text{C}$ accuracy with 20 Hz data rate. The technique is easily integrated to the current semiconductor processing chambers. It is insensitive to the process environment since the acoustic energy is confined to the wafer. Temperature tomography, developed based on the same technique, is used to calculate the temperature distribution on the wafer with an estimated accuracy of $\pm 5^\circ\text{C}$ with an achievable data rate of 2 images/sec with parallel processing. This information is very important for real time temperature control and process chamber design.

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