IN-SITU ACOUSTIC THERMOMETRY AND TOMOGRAPHY FOR RAPID THERMAL PROCESSING

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ABSTRACT

Temperature dependent velocity of acoustic waves guided by the silicon wafer is used to measure its temperature from 20°C to 1000°C with attainable accuracy of ±1°C The acoustic temperature sensor has been installed and tested in a rapid thermal processing environment. Temperature mapping is obtained by measuring the acoustic wave velocity along different paths on the wafer and applying tomographic inversion techniques.

INTRODUCTION

A key enabler of rapid thermal processing technology is the ability to measure and map the wafer temperature accurately. There are, however, currently no effective means of monitoring wafer temperature and its distribution over the wafer. While thermocouples provide a fairly precise measurement, they generally must contact the wafer, acting as a heat sink and creating a temperature non-uniformity. They can also react with the wafer at higher temperatures, contaminating it, and are incompatible with the harsh conditions (reactive gases, and high temperatures) present in the processing chambers. Optical pyrometers are non-contacting, 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.

The velocity of acoustic wave propagation in the silicon wafer (Lamb wave) is a fairly strong function of temperature, and this is exploited to obtain a reliable temperature measurement [1]-[3]. Demonstration of the acoustic temperature sensor from 20°C to 1000°C with ±1°C attainable accuracy, as well as a demonstration of tomographic techniques for temperature mapping are presented.

LAMB WAVES

Lamb waves are guided mode acoustic waves propagating along a plate with free boundaries (e.g. silicon wafer supported on quartz pins), with displacements occurring both parallel and perpendicular to the direction of wave propagation [2]. The two lowest order Lamb waves, the zeroth order symmetric and antisymmetric modes, are illustrated in Fig. 1. The actual displacements are in the order of a few Å. The dispersive nature of the fundamental Lamb waves are illustrated in Fig. 2.

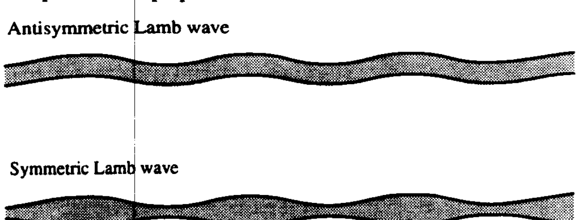

Fig. 1 Two zeroth order Lamb waves.

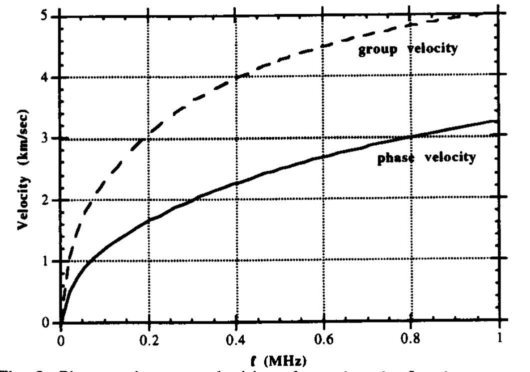

Fig. 2 Phase and group velocities of zeroth order Lamb wave as a function of frequency.

Among the various Lamb wave modes that can be generated in the wafer, the zeroth order antisymmetric mode (A0) is dominant in the acoustic temperature sensor. This mode is thus used for all measurements.

PRINCIPLE OF OPERATION

The set-up of the acoustic temperature sensor is shown in Fig. 3. Acoustic transducers with a center frequency of 300kHz are mounted at the bases of the quartz support pins. An

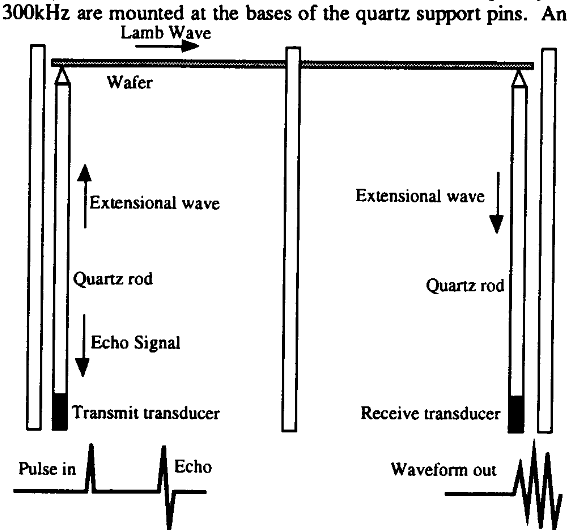

Fig. 3 Set-up of the acoustic temperature sensor.

* Work was performed while a graduate student at Stanford University.

electrical pulse applied across the transducer generates an extensional mode acoustic wave in the quartz pin. The acoustic pulse travels up the quartz pin and is converted into Lamb wave in the wafer at the Hertzian contact. The Lamb wave propagates out from the contact point toward the transducer pin at the opposite side of the wafer where it is again converted into an extensional mode in the quartz rod. The wafer is placed so that the acoustic wave propagation is measured along the (100) crystallographic orientation of the wafer. The extensional mode acoustic wave at the opposite pin is detected by the transducer attached at the base of the pin. At the same time, the pulse-echo signal of the acoustic wave propagating up the quartz rod and reflected off the Hertzian contact back into the rod is also detected. The time of flight of the pulse-echo signal is effectively subtracted from the total time of flight to obtain the temperature dependent time of flight of the Lamb wave across the wafer.

MEASUREMENT ELECTRONICS

In terms of electronic implementation, the subtraction is performed by using a zero crossing on the pulse echo signal to start the counter, and a zero crossing on the total time of flight signal to stop the counter (Fig. 4). The measurement computer uses the measured time of flight data to determine the position of the *Enable Counter Start* and *Enable Counter Stop* signals.

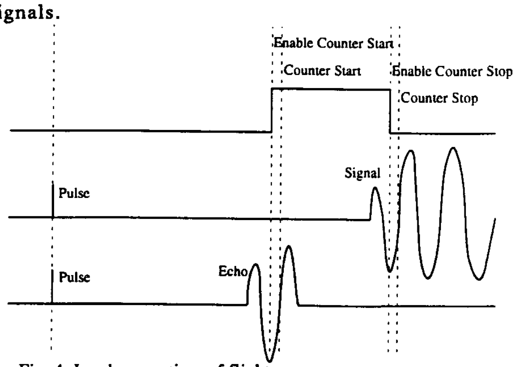

Fig. 4 Lamb wave time of flight measurement.

The Majority of the electronics used for the sensor are in the form of standard measurement equipments controlled through the General Purpose Interface Bus (GPIB) as shown in Fig. 5. The computer inputs the initial positions of the *Enable Counter Start* and *Enable Counter Stop* values into the delay generator. The delay generator sends a rising edge signal into a pulser/receiver which sends out a pulse into the transducer pin. The pulse echo signal is detected and amplified by the pulse/receiver and the signal is sent to the time interval counter. After the counter has been armed by the *Enable Counter Start* signal, the pulse/echo signal triggers the start of the counter. Roughly 35μsecs later, a trailing edge *Enable Counter Stop* signal is sent to the time interval counter. At about the same time, the total time of flight signal is detected at the opposite transducer pin. The signal is amplified using the low-noise pre-amplifier, and the signal is used to stop the counter. The time interval counter then sends the effective time of flight of the Lamb wave into the computer through the GPIB bus. The Lamb wave time of flight signal is used to obtain the temperature of the wafer and is also used to update the values of the *Enable Counter Start* and *Enable Counter Stop* signals. A thermocouple monitor is used to record the temperature of the wafer during calibration and test runs.

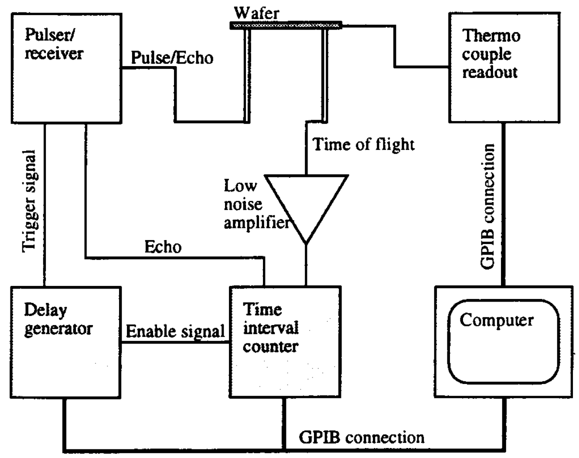

Fig. 5 Electronic measurement system.

The repetition rate of the pulse/data-acquisition is determined by the decay time of multiple reflections in the wafer. It has been found experimentally that the wafer resonance signal becomes undetectable about 50msecs after the initial pulsing of the excite transducer. Data rate (i.e. pulse rate) of 20Hz is thus used.

TRANSDUCER PINS

Wafers in most rapid thermal processors are supported on quartz pins during processing. The low thermal conductivity of quartz and the small contact area prevent heat transfer from the wafer into the support pins, thus avoiding temperature non-uniformities. The quartz pins used in the acoustic temperature sensor are circular in cross section with a diameter of 1.5mm and a length of 17.5 cm. The tips of the pins are sharpened into a point and the top is rounded with a radius of 100μm. The spherical tip insures a single, reproducible Hertzian contact with the silicon wafer. Lead Zirconium Titanate (PZT) 5H is used as the transducer material. The cylindrical PZT has the same radius as the quartz pin and is 4mm long with the direction of polarization along its length. The ends of the PZT, as well as the flat end of the quartz rod are metalized (with gold or aluminum). Part of the side of the quartz rod at the flat end is also metalized to provide an electrical contact pad. Besides providing an electrical contact to the PZT, the metalization at the end of the quartz rod protects the PZT from radiation that is guided by the quartz rod. The high reflectivity of the metalization ensures that most of the radiation energy is reflected off the quartz-PZT interface. The PZT is attached onto the quartz rod using an epoxy bond, and electrical contacts are made at the bottom of the PZT and at the metalized side of the quartz rod.

TRANSDUCER MODULE

The transducer pins are housed in a cylindrical chamber and are supported by viton o-ring feedthroughs. The exact length of the pins extending out of the transducer housing can be adjusted by loosening the o-rings around the pins and sliding them up or down. The o-ring pressure required to hold vacuum introduces between 10% to 20% one-way loss in acoustic energy depending on the tightness of the seal. The general waveform, however, remains the same. Care must be taken to insure that there are no direct contacts between the chamber and the pins in the feedthroughs as it causes significantly larger (>50%) losses in acoustic energy.

A pneumatically operated bellows system brings the transducer housing and inner chamber into a lowered position for manual loading of the wafer. Because the wafer is loaded into the chamber manually, three guide pins extending above the support pins by about 2mm are needed to guide the user in placing the wafer. During processing, the transducer assembly is raised and the wafer is brought about 3mm below the top quartz window for efficient heating. The wafer rests freely on the three pins without any clamping mechanism.

The transducer chamber ambient is isolated from the processing ambient to protect the transducers from the harsh reactants and high temperatures. The isolation also prevents the contamination of the processing environment by the transducer material. The chamber is made of aluminum due to its ease of machinability. After polishing, the outer surface of the transducer housing was plated with nickel to minimize the absorption of the lamp radiation. The bottom of the chamber is removable so that there is access to the transducers. The bottom cover has vacuum compatible feedthroughs for Teflon jacketed coaxial cables, gas lines, and thermocouple probes. The coaxial cables carry the excitation and detection electrical signals. The gas lines allow the flow of nitrogen into the system to regulate the temperature of the chamber ambient. The thermocouple probe is used to monitor the temperature of the ambient.

Excessive flow of nitrogen, while keeping the chamber cool, causes significant turbulence which is picked up as noise by the transducers. A flow setting which maintains the chamber temperature at about 50°C during high temperature runs has been found to be optimal.

CALIBRATION PROCEDURE

A calibration is made with a c-type reference thermocouple welded onto the center of the wafer to experimentally determine the temperature dependence of Lamb wave velocity in silicon along the (100) crystallographic direction (Fig. 6). The calibration is made for steady-state conditions with constant lamp power settings to eliminate the dynamic effects of temperature distribution over the wafer. The lamp power settings at 0%, 20%, 40%, and 60% are used. All excitation and measurement techniques are kept identical to actual measurement conditions. A fourth order polynomial model for the temperature dependent velocity was then obtained from regressional analysis (Fig. 7).

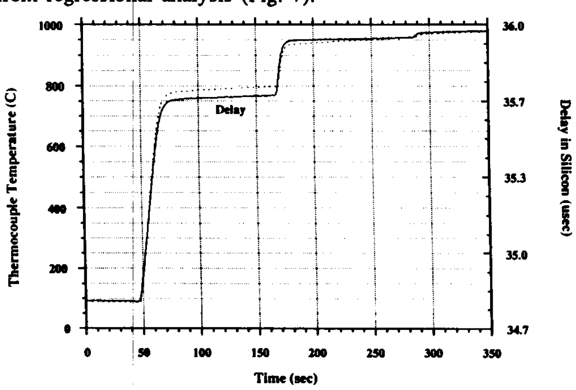

Fig. 6 Calibration run performed with a reference thermocouple.

Because the time of flight measurement is based on measuring the zero-crossing of a particular waveform within a wave train, both the phase and group velocities are involved in the measurement. The group velocity is involved in carrying the wavetrain to the point of detection, while the phase velocity of the waves within the envelope determines the position of the zero crossings. The measured velocity value of roughly 2450m/sec at room temperature is between the theoretical phase and group velocities (Fig. 2). The average relative velocity dependence obtained experimentally is about 38ppm/°C.

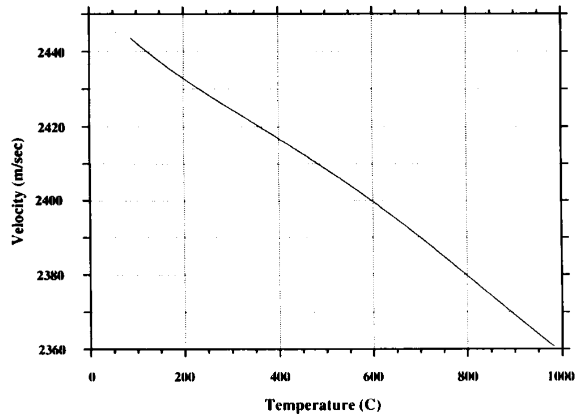

Fig. 7 Effective velocity as a function of temperature.

MEASUREMENTS IN RTP

The polynomial model (Fig. 7) was applied to a dynamic temperature ramp-up and ramp-down in a rapid thermal processor. Acoustic thermometry requires no thermal mass contacting the wafer and thus has a faster response time than the reference temperature taken with a type-c thermocouple welded onto the center of the wafer. The difference in the ramp-up and ramp-down transients between acoustic and thermocouple measurements, however, is primarily due to the fact that the wafer edges respond faster to temperature control than the wafer center. Due to the triangular position of the transducer pin contact points, the acoustic temperature sensor effectively

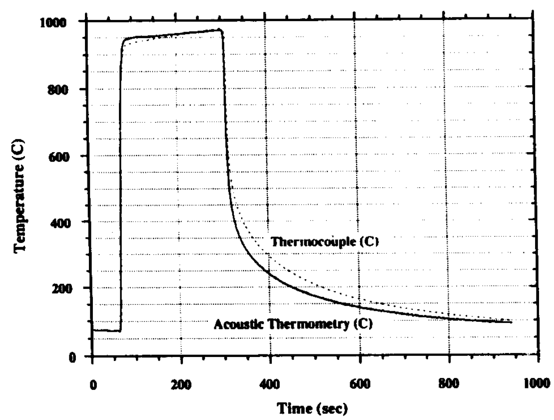

Fig. 8 Performance of the acoustic temperature sensor. Difference during the transients are due to the slower response of the thermocouple and the different positions of the thermocouple and acoustic path.

measures the temperature of the wafer off its center point. The acoustic temperature measurement is compared with thermocouple data in Fig. 8. Accuracy of ±5°C was obtained.

ATTAINABLE ACCURACY

The signal to noise ratio (S/N) of the measurement system is a function of several parameters. One of the most important is the contact force between the pin and the wafer which can be controlled in a system with spring-loaded pins. Fig. 9 shows the measured standard deviation of temperature measurement as a function of the measured S/N of the system. Accuracy of ±1°C is attainable when S/N is greater than 47dB.

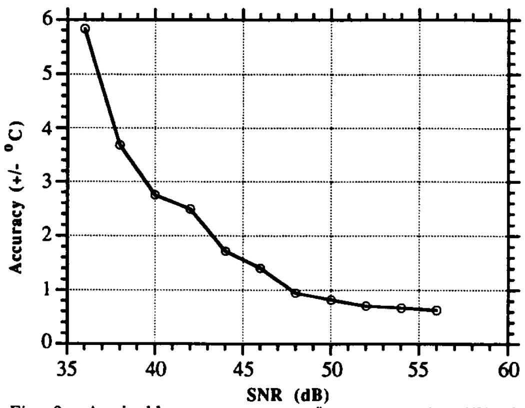

Fig. 9 Attainable accuracy as a function of the S/N of the measurement system

TEMPERATURE MAPPING

Temperature mapping is obtained by placing an array of transducer pins around the periphery of the wafer. By obtaining time of flight data across different paths on the wafer and applying "fan beam" tomographic inversion techniques, temperature maps of the wafer are obtained [4]. Since more than three pins are used, the weight of the wafer can no longer be used to obtain reliable Hertzian contacts. A spring-loaded set of larger diameter transducer pins (3mm) are used.

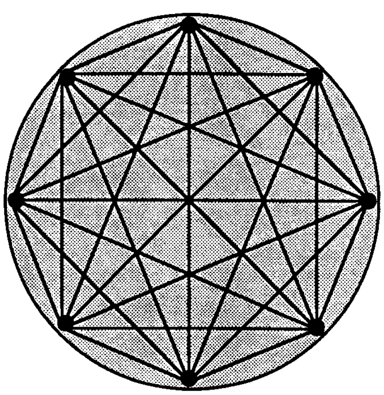

Fig. 10 Lamb wave paths for temperature mapping.

Using 8 pins, time of flight measurements along 28 different paths can be made (Fig. 10). Lamb wave velocity and its temperature dependence are a function of the direction of propagation with respect to the crystallographic orientations. Calibration procedure illustrated in Figs. 6 and 7 are performed for each path with temperature uniformity maintained over the wafer.

The Texas Instruments designed rapid thermal processor has circularly symmetric heating lamps with controllable zones arranged in concentric rings. Temperature mapping data with the assumption of circular symmetry is thus needed for real-time temperature uniformity control.

Demonstration of a four-zone circularly symmetric temperature mapping is shown in Fig. 11. A large circularly symmetric temperature non-uniformity was intentionally introduced over the wafer by masking the lamp radiation on the wafer except in a central area. Acoustic temperature mapping obtained during steady state conditions compares well with thermocouples welded onto the wafer at various locations.

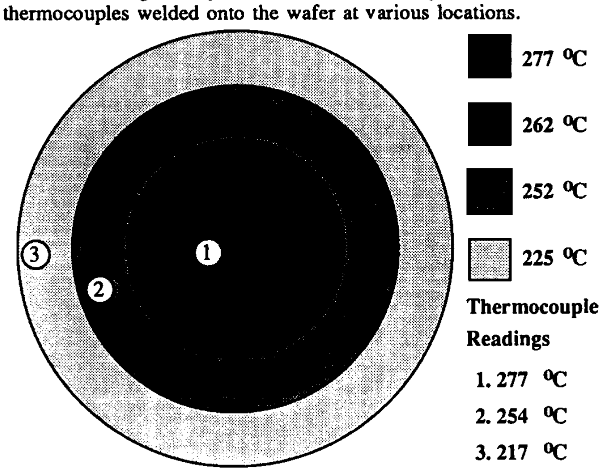

Fig. 11 Temperature mapping data.

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