Temperature measurement in rapid thermal processing using acoustic techniques

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Acoustic techniques are used to monitor the temperature of silicon wafers during rapid thermal processing from room temperature to 1000 °C with ±5 °C accuracy. Acoustic transducers are mounted at the bases of the quartz pins that hold up the silicon wafer during rapid thermal processing. An electrical pulse applied across a transducer generates an extensional mode acoustic wave guided by the quartz pins. The extensional mode is converted into Lamb waves in the silicon wafer which acts as a plate waveguide. The Lamb waves propagate across the length of the silicon wafer and are converted back into an extensional mode in the opposite pin. The time of flight of the extensional mode in the quartz pins is measured using pulse echo techniques and is subtracted from the total time of flight to obtain the Lamb wave time of flight across the wafer. Because the velocity of Lamb waves in the silicon wafer is systematically affected by temperature, the measurement of the time of flight of the Lamb wave provides the accurate temperature of the silicon wafer.

I. INTRODUCTION

One of the key requirements for rapid thermal processing is the ability to accurately monitor and control the temperature of the wafer during its thermal cycles. Current methods of temperature measurement, however, have significant limitations.[1] Pyrometric temperature measurements which are most widely used in rapid thermal processing are affected by variations in wafer emissivity and by heating lamp radiation interference. Although thermocouples provide a more reliable temperature measurement, a good thermal contact with the wafer is needed. The thermal contact with wafer, however, creates a cold spot at the wafer and creates problems with wafer contamination at high temperatures. Thermocouple junctions are also degraded by the harsh processing conditions of the processing chamber.

The acoustic temperature sensor provides temperature measurement that is independent of wafer emissivity conditions and lamp radiation levels. It does not require thermal contacts on the wafer and is compatible with the reactive conditions of rapid thermal processing.

II. 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 prevents heat transfer from the wafer into the support pins thus avoiding temperature nonuniformities. The quartz pins used in the acoustic temperature sensor are circular in cross section with a diameter of 1.5 mm 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 100 μm. The spherical tip ensures 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 4 mm long with the direction of polarization along its length. The ends of the PZT, as well as the flat end of the quartz rod is metallized with gold. Part of the side of the quartz rod at the flat end is also metallized with gold to provide an electrical contact pad. Besides providing an electrical contact to the PZT, the gold metallization at the end of the quartz rod protects the PZT from radiation that is guided by the quartz rod. The high reflectivity of gold 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 metallized side of the quartz rod. A protective enclosure is attached around the PZT and low vapor pressure silicone is injected into the enclosure to encapsulate the transducer and the wire bonding pads. A vacuum compatible coax cable with a Teflon jacket is brought out of the enclosure.

III. TRANSDUCER MODULE

The transducer pins are housed in a cylindrical chamber and are supported by 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 does introduce some losses to the acoustic wave propagation in the quartz rods but not to a significant extent. The bottom of the chamber is removable so that access can be made to the transducers. The bottom cover has vacuum compatible feedthroughs for the coaxial cables that carry the signals to and from the transducers. The module is designed to operate with either a cooling gas or liquid in the chamber to maintain the transducers at a constant temperature.

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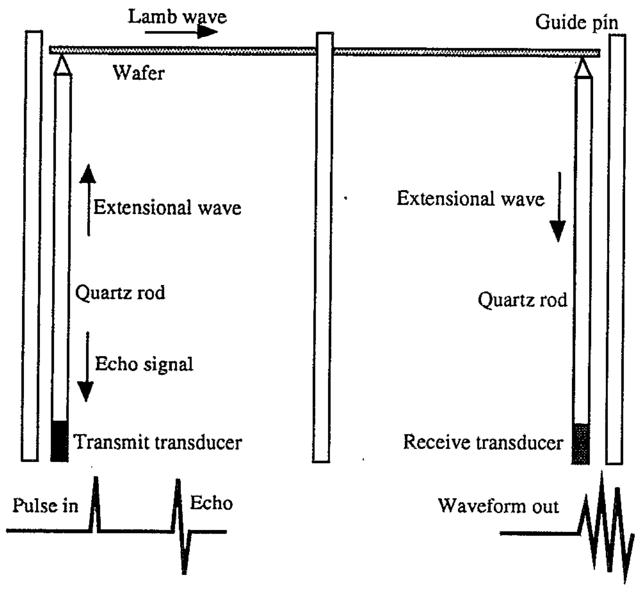

FIG. 1. Setup for measurement of silicon wafer temperature using acoustic techniques. The quartz support rod is used to transmit and receive acoustic waves. The guide pins prevent the wafer from falling off the pins during placement of the wafer in the reaction chamber.

IV. TIME OF FLIGHT MEASUREMENT

The time of flight measurement is described in Fig. 1. An 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 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.[2,3] The extensional mode acoustic wave at the opposite pin is detected by the transducer attached at the base of the pin. The time of flight between the pulsing of the excitation transducer and a zero crossing on the received signal is measured. 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 measured. 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 in the wafer.[4,5] In terms of electronic implementation, the subtraction can be performed in two ways. In the first method, two separate time delay measurements for the total time of flight and pulse echo are measured, and the pulse echo is subtracted from the total time of flight on a computer. In the second method, a zero crossing on the pulse-echo signal is used to start the counter, and a zero crossing on the total time of flight signal is used to stop the counter (Fig. 2). In both methods, the computer uses the measured time of flight data to control the position of the counter start enable and counter stop enable signals on the time interval counter.

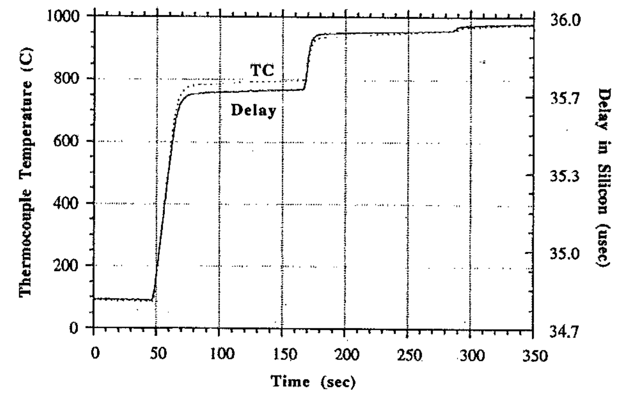

FIG. 3. Calibration run used to determine the Lamb wave velocity as a function of wafer temperature is steady state conditions.

V. MEASUREMENT

A calibration is made with a reference thermocouple that is welded onto the center of the wafer to experimentally determine the temperature dependence of Lamb wave

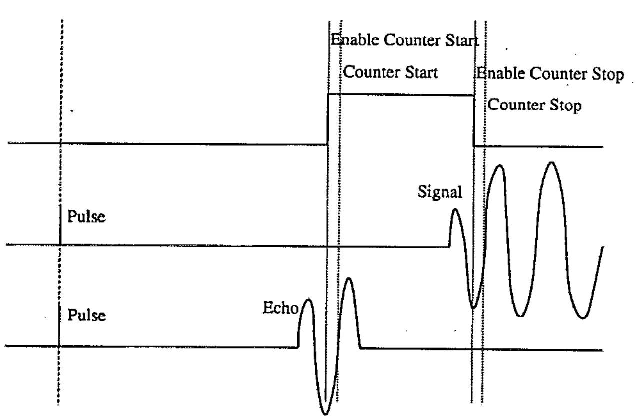

FIG. 2. Timing diagram for deriving time of flight of Lamb wave where pulse-echo signal is used to start the time delay counter and a specified zero crossing of the total time of flight signal is used to stop the counter.

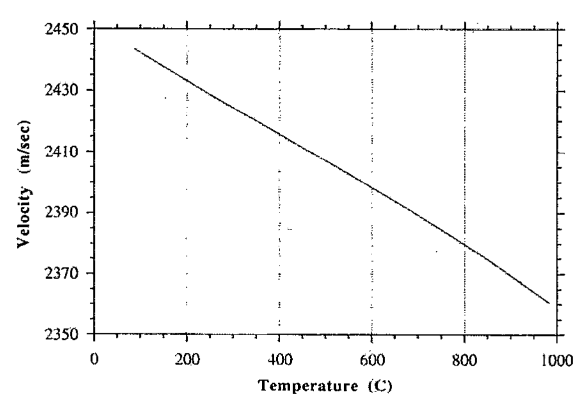

FIG. 4. Fourth-order polynomial model of the temperature dependent Lamb wave velocity given by $T=413\,870\,0+4479.1v-1.289\,67v^2-5.8480\times10^{-5}v^3+4.9016\times10^{-8}v^2$, where T is the temperature and v is the measured Lamb wave velocity.

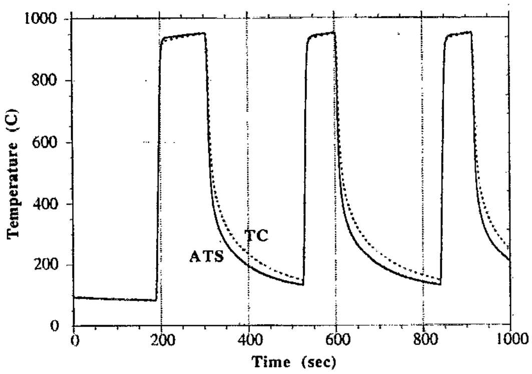

FIG. 5. Comparison of the acoustic temperature sensor (solid line) and reference thermocouple (dotted line) welded onto the center of the wafer.

velocity in silicon along the (100) crystallographic direction (Fig. 3). The calibration is made for steady-state conditions with a constant heating-lamp power setting to eliminate the dynamic effects of temperature nonuniformities in the wafer. A fourth-order polynomial model for the temperature dependence was then obtained from the calibration run and used to convert time of flight into temperature (Fig. 4).

The polynomial model 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 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 measures the temperature of the wafer off its center point while the thermocouple is welded at the center. The acoustic temperature measurement which is made at a 10 Hz data rate is compared with the thermocouple data in Fig. 5.

We have demonstrated a novel ultrasonic thermometer for sensing, *in situ*, the temperature of silicon wafers. Presently, the ultrasonic thermometer is capable of measuring with an accuracy of ± 5 °C. Further improvements in system implementation can easily improve the accuracy to ± 1 °C.

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