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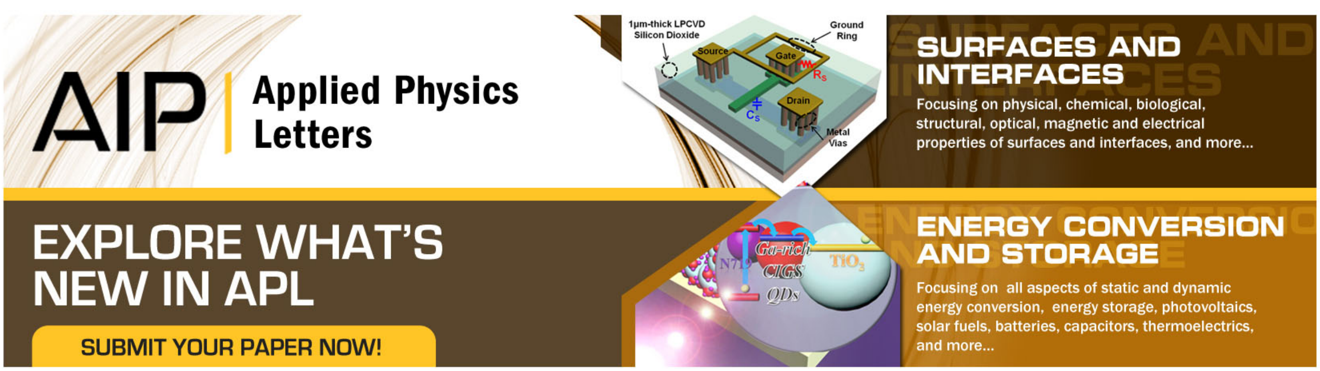

In situ thin film thickness measurement with acoustic Lamb waves

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In situ thin film thickness measurement is an important problem in semiconductor processing, which is currently limited by the lack of adequate sensors. Most of today's available techniques are restricted to certain type of films and many have difficulties in performing the measurement *in situ*. The fact that the velocity of an ultrasonic Lamb wave traveling in a silicon wafer is changed by the thin film coating on the wafer surface can be used as a monitoring method for basically any type of film—opaque, transparent, metal, or insulator. The acoustic sensors are easily implemented into plasma or CVD environments. We have demonstrated the technique in an aluminum sputtering system in which we measure Al film thickness with a resolution of ±100 Å. Even better resolution can be achieved for SiO_2, copper, and tungsten films. This system has a variety of potential applications, not only in film thickness measurement, but also in characterization of film properties and multilayer deposition process control. © *1995 American Institute of Physics.*

In situ thin film thickness monitoring is an important problem in semiconductor process control, monitoring, and optimization. Various thin film measurement methods, such as surface profilometry and resistivity measurements, are very difficult to carry out *in situ*, and analysis of film growth rate is usually performed after the deposition run. Currently, ellipsometry is preferred as an *in situ* monitoring tool.[1,2] However, it lacks the ability to measure opaque films, and deposition hardware frequently does not have the proper viewport for the probing beam.[3] Quartz crystal monitors are also available as an *in situ* monitoring tool, but they only offer an indirect measurement of the film thickness grown on the wafer surface. To overcome these limitations, we have developed a new *in situ* thin film measurement technique utilizing ultrasonic Lamb waves. The Lamb waves are excited and propagate through the silicon wafer, and the film thickness is directly related to the wave velocity. This is a noninvasive method, and the measurement is not limited by the optical or electrical properties of the thin film. The new sensor system is compatible with most plasma or chemical vapor deposition (CVD) environments. In this work, we demonstrated the validity of this approach by measuring thickness of aluminum films.

Theoretical calculations indicate that the velocity of the zeroth order antisymmetric Lamb wave propagating through a silicon wafer is changed by a thin film coating on the wafer surface.[4] Figure 1 shows the calculated phase velocity change along the ⟨100⟩ direction as a function of thickness for various films on a 500-μm-thick silicon wafer. The frequency of operation is at 200 kHz. The phase velocity increases with the growth of Al and SiO_2 films and decreases with Cu film. The change remains linear up to a few micrometers of film thickness. The variation of the wave velocity is well within experimental measurement sensitivity.

The Lamb wave is excited using a piezoelectric transducer bonded to a 5-cm-long fused quartz rod, which goes through the wafer chuck. The tip of the quartz rod is rounded with a radius of curvature of 100 μm. The spherical tip gives a point contact to the back side of the silicon wafer, and the transducer/quartz rod assembly is spring-loaded to ensure table contacts very time a new wafer is loaded onto the chuck (Fig. 2). An identical transducer/quartz pin set is used as a receiver to detect the Lamb wave transmitted through the substrate. Because silicon is an anisotropic material, we use the wafer flat as the orientation reference to align the transmitter/receiver along the ⟨100⟩ direction in order to obtain maximum sensitivity. Lead zirconium titanate (PZT) 5H is used as the transducer material and the resonant frequency set to 200 kHz with 40% fractional bandwidth. The transducers are protected by vacuum tight metal housings so that the PZT is not exposed to the sputtering environment. Signals from the receiver are preamplified and then brought out of the vacuum chamber.

The time of flight measurement is described in Fig. 3. An electrical impulse of 500 V is applied to the transmitter, which generates an extensional mode in the quartz rod. At the quartz pin tip wafer contact, part of the extensional mode

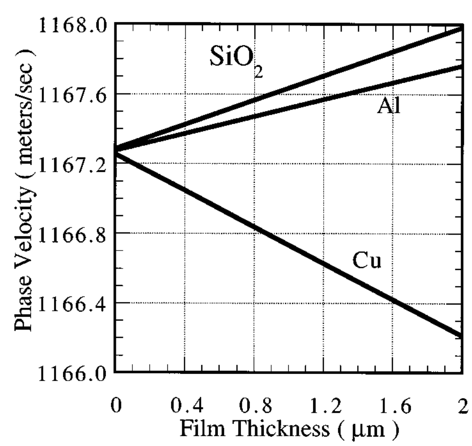

FIG. 1. Antisymmetric Lamb wave phase velocity vs thin film thickness. The frequency of operation is 200 kHz.

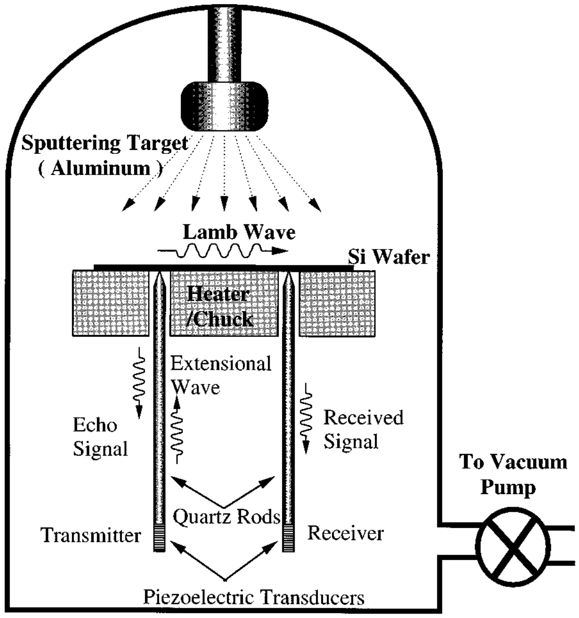

FIG. 2. *In situ* acoustic sensors implemented inside aluminum sputtering station.

energy is reflected back to the transducer and generates an echo electrical pulse, and the other part of the energy is coupled into the wafer as the zeroth order antisymmetric Lamb wave is excited. After propagation through the wafer, the Lamb wave is converted back to an extensional mode at the receiver tip, and then to an electrical signal in the receiving transducer. The pin-to-pin time of flight is measured by monitoring the time interval between the transmitter echo and the receiver signal. The first zero crossing of the echo signal triggers the start of the time delay counter and the first zero crossing of the transmitted the signal stops the counter. The time delay measured is the time that takes the Lamb wave to travel through the silicon wafer from the transmitter tip to the receiver tip. The effect of the quartz pins is eliminated due to the subtraction of the time delay in the quartz rods from both transmitter and receiver.

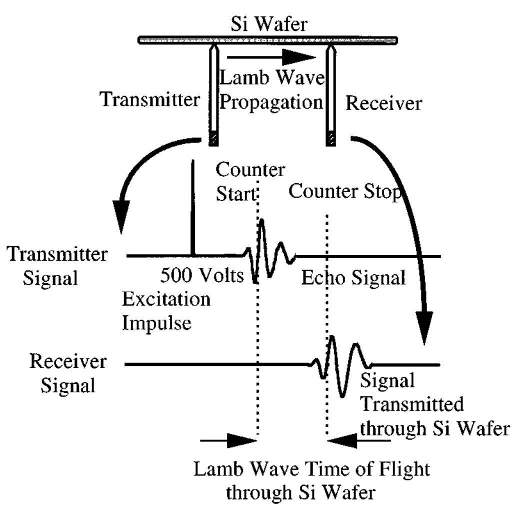

FIG. 3. Timing diagram for measuring time of flight of Lamb waves. The zero crossing of echo signal and the transmitted signal trigger the start and stop of the time counter.

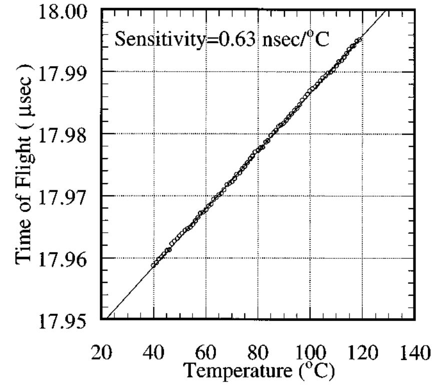

FIG. 4. Time of flight changes vs substrate temperature. The coefficient obtained is used to correct the time of flight data in the film thickness measurement.

The acoustic sensor system is implemented in an aluminum sputtering system. It is calibrated to have an Al deposition rate of 400 Å/min. If the silicon wafer temperature is constant during processing, the time of flight should decrease as aluminum is sputtered on the wafer surface. However, in our present system, there is some temperature rise as the plasma heats the substrate. Since the elastic constants of silicon also change with temperature,[5,6] it is essential to subtract the change in the time of flight that is due to temperature variation during processing. This calibration is done by determining the temperature sensitivity using the same set of sensors. Figure 4 shows the time of flight change as the silicon wafer is heated, which exhibits a linear dependency with temperature. Thus, the effect of temperature can be subtracted to yield the time of flight due to film deposition.

Figure 5 shows a typical sputtering run of 30 min while 1.12 μm of Al film is deposited. Sputtering starts at 10 min and stops at 40 min. During sputtering, a thermocouple is employed to monitor the temperature of the wafer. The time of flight data are corrected with the predetermined temperature sensitivity coefficient. The resolution of the film thickness is mainly determined by the signal to noise ratio (SNR) of the received signal (Fig. 6). Special care is taken to sepa-

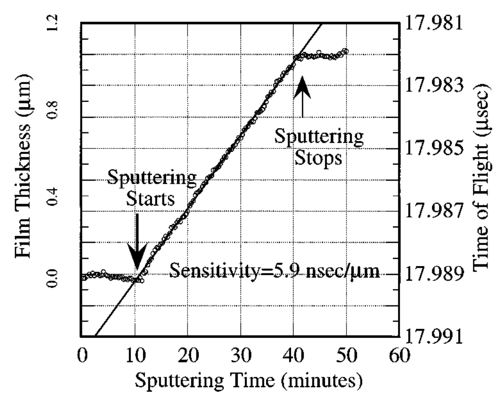

FIG. 5. *In situ* thin film thickness measurement. Time of flight decreases linearly during a 30 min run while 1.2 μm of Al film is grown.

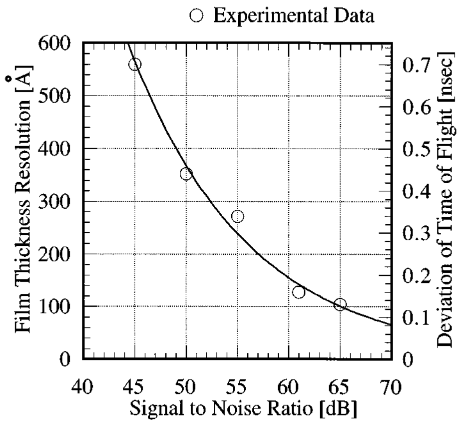

FIG. 6. Film thickness measurement accuracy as a function of SNR.

rate the signal and chassis grounds to prevent ground noise. An ultralow noise (4 μV/$\sqrt{\text{Hz}}$) preamplifier is used immediately after the receiver and the signal is amplified by 30 dB before it travels out of the sputtering chamber. A time delay counter SR620 from Stanford Research System is used to measure the time of flight. This type of time counter has a time resolution of 25 ps single shot. With better than 65 dB of SNR, the standard deviation of the time of flight is less than 0.12 ns, which translates into a thickness measurement resolution of better than $\pm$100 Å.

Precise control of film thickness is becoming increasingly important in the semiconductor industry, and an *in situ* thickness sensor is an essential element in performing the close loop control of manufacturing processes. We have demonstrated a novel technique for *in situ* thin film thickness measurement using ultrasonic waves. The acoustic sensor system can be easily implemented into existing industrial processing equipment. The low thermal conductivity of the quartz pins ensures that they do not introduce significant heat transfer during processing. The acoustic energy is confined in the silicon wafer, therefore, the measurement is insensitive to the processing environment such as pressure or gas species. The measurement does not depend on the optical or electrical properties of the deposition material, therefore, it can be used to monitor opaque, transparent, metal or nonconductive films. With proper calibration, the sensor can also be used in film property characterization, multilayer deposition, and real-time process control.

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