

# IN-SITU THIN FILM THICKNESS MEASUREMENT USING ULTRASONICS WAVES

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## ABSTRACT

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. We excite and detect Lamb waves using PZT transducers on one end of quartz buffer pins that are in contact with the back side of the wafer. The time of flight of the ultrasonic wave is calculated and measured to be linearly related to the film thickness. The acoustic sensors is easily implemented into plasma or CVD environments. We have demonstrated the technique in an aluminum sputtering system. We measure Al film thickness with a resolution of  $\pm 100\text{\AA}$ . Even better resolution can be achieved for  $\text{SiO}_2$ , copper and tungston films. This system has a variety of potential applications not only in film thickness measurement, but also in characterization of film property and multi-layer deposition process control.

### Motivation for Acoustic Thickness Sensors

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 measurement 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 viewpoint 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 non-invasive 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 CVD environments. In this work, we demonstrated the validity of this approach by measuring thickness of aluminum films.

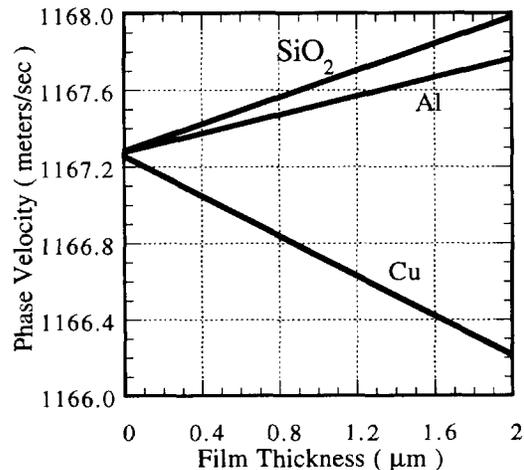


Fig. 1. Antisymmetric Lamb wave phase velocity vs. thin film thickness. The frequency of operation is 200kHz.

### Lamb Wave Propagation and Time of Flight Measurement

Theoretical calculations indicate [4] 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. Fig. 1 shows the calculated phase velocity change along the  $\langle 100 \rangle$  direction as a function of thickness for various films on

a 500 $\mu\text{m}$  thick silicon wafer. The frequency of operation is at 200kHz. The phase velocity increases with the growth of Al and SiO<sub>2</sub> films and decreases with copper film. The change remains linear up to a few microns of film thickness. The variation of the sound speed is well within experimental measurement sensitivity.

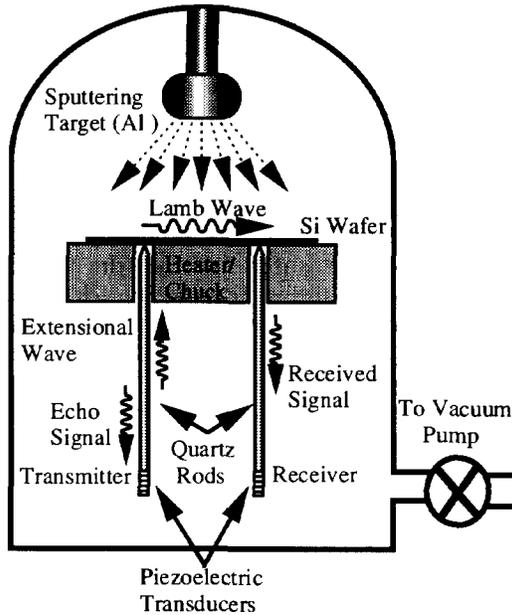


Fig. 2. In-situ acoustic sensors implemented inside aluminum sputtering station.

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 $\mu\text{m}$ . 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 stable contacts every 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 Si is an anisotropic material, we use the wafer flat as the orientation reference to align the transmitter/receiver along the  $\langle 100 \rangle$  direction in order to obtain maximum sensitivity. Lead Zirconium Titanate (PZT) 5H is used as the transducer material and the resonant frequency set to 200kHz 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.

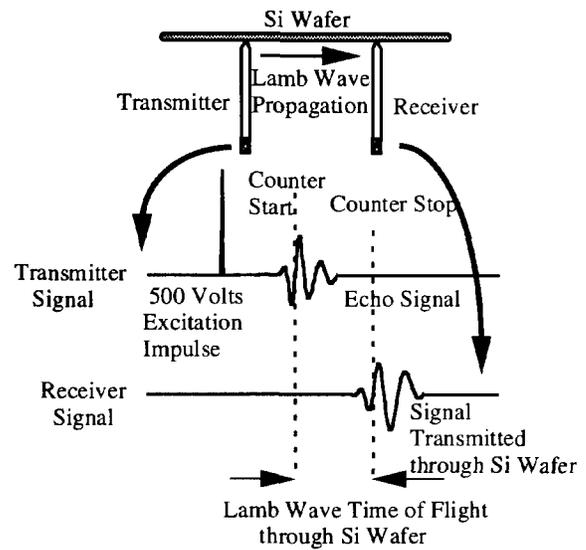


Fig. 3. Timing diagram for measuring time of flight of Lamb waves. The zero crossing of echos signal and the transmitted signal trigger the start and stop of the time counter.

An electrical impulse of 500 volts 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 energy is reflected back to the transducer and generates an echo electrical pulse, 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 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.

### In-Situ Thickness Measurement

The acoustic sensor system is implemented in an aluminum sputtering system. It is calibrated to have an Al deposition rate of 400  $\text{\AA}/\text{min}$ . 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

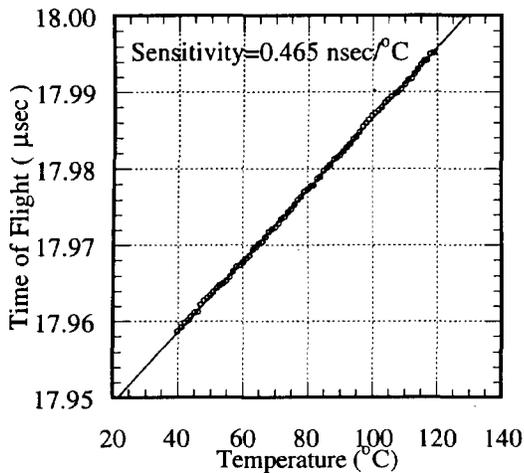


Fig. 4. Time of flight changes vs. substrate temperature. The coefficient obtained is used to correct the time of flight data in the film thickness measurement.

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. Fig.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.

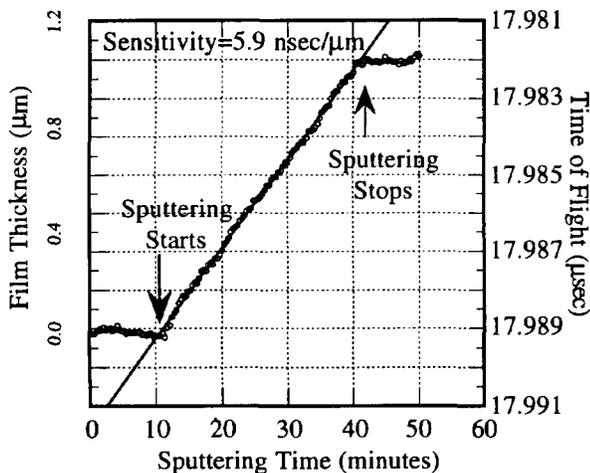


Fig. 5. In-situ thin film thickness measurement. Time of flight decreases linearly during a 30-minute run while 1.2µm of Al film is grown.

Fig.5 shows a typical sputtering run of 30 minutes while 1.12µm of Al film is deposited. Sputtering starts at 10 minutes and stops at 40 minutes. During sputtering, a thermocouple is employed to monitor the temperature of the wafer. The time of flight data is 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 separate the signal and chassis grounds to prevent ground noise. An ultra-low noise (4µVolts/√Hz) preamplifier is used immediately after the receiver and the signal is amplified by 30dB 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 picosecond single shot. With better than 65dB of SNR, the standard deviation of the time of flight is less than 0.12 nsec, which translates into a thickness measurement resolution of better than ±100Å.

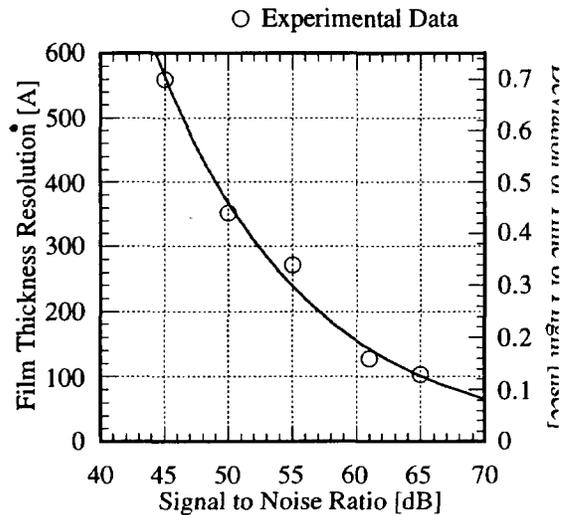


Fig. 6. Film thickness measurement accuracy as a function of SNR.

### Conclusion

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, multi-layer deposition and real-time process control.

#### **Acknowledgment**

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