In situ simultaneous measurement of temperature and thin film thickness with ultrasonic techniques

by

Butrus T. Khuri-Yakub, Jun Pei, F.Levent Degertekin,
and Krishna C. Saraswat*

Edward L. Ginzton Laboratory
Stanford University, Stanford, CA 94305

*Center for Integrated Systems,
Stanford University, Stanford, CA 94305

ABSTRACT

We describe a novel technique to measure *in situ*, simultaneously, temperature and thin film thickness during semiconductor processing. The measurement is based on the principle that the velocity of an ultrasonic Lamb wave propagating in a silicon wafer is a function of both the wafer temperature and the thin film coating on the wafer surface. Because sensitivities of Lamb wave velocity to temperature and film thickness change differently with frequency, with a simple linear inversion method, we are able to obtain both the processing temperature and film thickness simultaneously with two sets of sensors operating at two distinct frequencies, 0.5MHz and 1.5MHz. This technique is demonstrated in an aluminum sputtering system. We have achieved a temperature measurement accuracy of ±0.15°C and an aluminum film thickness resolution of ±170Å. The measurement does not depend on the optical or the electrical properties of either the wafer or the film material, and is insensitive to the processing environment. With its high measurement accuracy and setup simplicity, this sensor system carries great potential in semiconductor process monitoring and control.

INTRODUCTION

In situ measurement of processing parameters has become increasingly important as integrated circuits (IC) feature size steadily shrinks and close-looped process control becomes more critical in many stages of IC manufacturing. Many of today's technological advances in processing are limited by the lack of adequate *in situ* temperature and film thickness sensors. Ultrasonic sensors utilizing Lamb wave propagation in silicon wafers has been reported to measure temperature in a wide range with high accuracy[1,2]. In this paper, we further advance this technology to perform *in situ* measurement of temperature and thin film thickness simultaneously. We demonstrate the ability of achieving an accuracy of ±0.15°C in temperature and ±170Å in film thickness in an aluminum film deposition process with a sputtering station. The temperature measurement in this technique still enjoys the benefit of wide range with no dependence on wafer emisitivity, which is the limiting factor in many pyrometer-based sensors. The sensors are also practically suitable to any type of film, regardless of its optical or electrical properties. This makes this measurement technique a very valuable tool in real-time wafer to wafer process monitoring, compensation of equipment drifts and diagnosis of system status.

THIN FILM EFFECT ON A_0 MODE LAMB WAVES

A silicon wafer is an anisotropic plate in which many modes of acoustic Lamb waves can be excited[3]. Fig. 1 shows the phase velocity dispersion relations of the first few modes of Lamb waves in a silicon wafer. At very low frequencies, only two modes exist, the symmetric S_0 mode and the anti-symmetric A_0 mode. The acoustic transducers are chosen to selectively excite the A_0 mode[4]. The A_0 mode Lamb wave velocity is a function of

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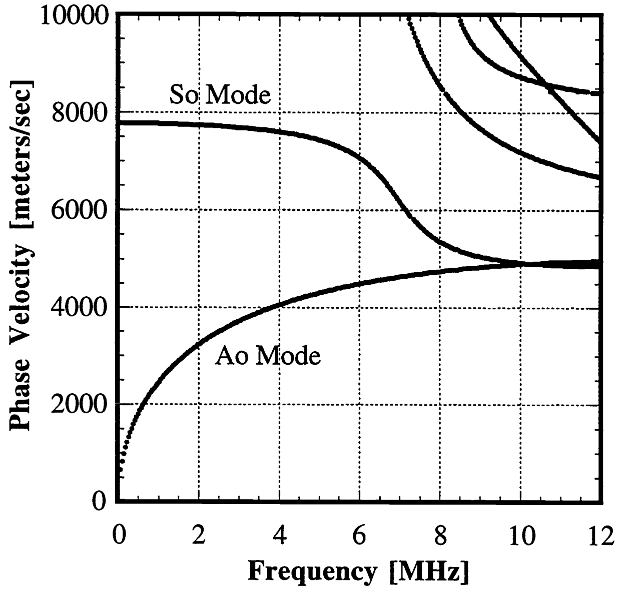
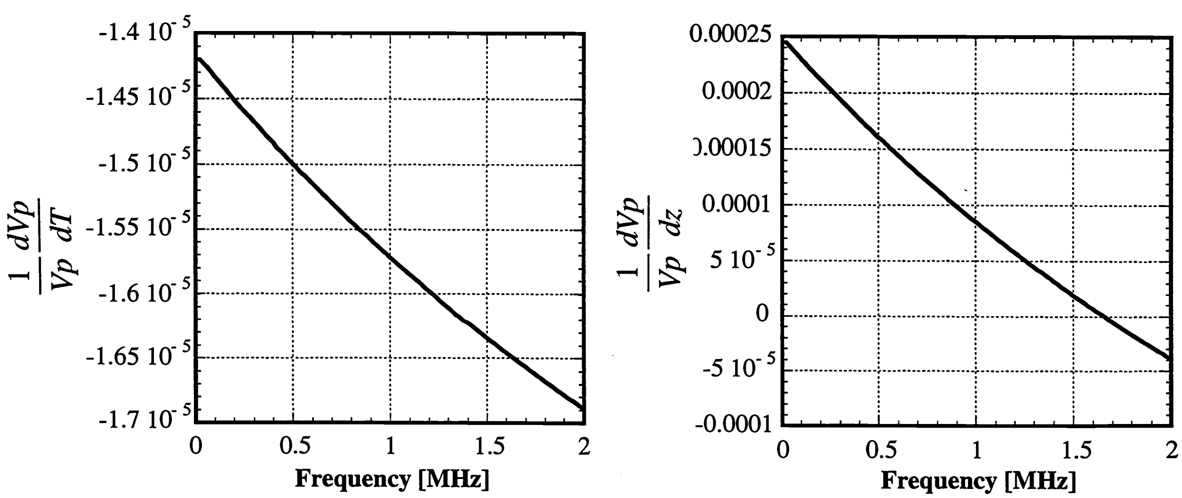


Fig. 1. Phase velocity dispersion relation of a 0.5mm thick silicon wafer along <100> direction. We operate at low frequency region where only two modes, So and Ao mode, can exist.



(a) (b)

Fig. 2. (a)Theoretical calculation of Ao mode phase velocity temperature dependency. The fractional change of Vp due to temperature variation does not change much with frequency. (b)The fractional change of Ao mode phase velocity as 1μm of aluminum film is deposited on a silicon wafer. The film dependency varies significantly with frequency. The zero crossing at about 1.6MHz implies that the phase velocity does not change as aluminum film is deposited.

temperature because the silicon elastic constants change with temperature[5]. Fig. 2(a) shows the fractional change of the A_0 mode Lamb wave velocity along the <100> direction vs. temperature in a 0.5mm thick silicon wafer. This temperature coefficient is roughly one order of magnitude larger than the thermal expansion coefficient, which implies that this mode is highly sensitive to temperature change. The A_0 Lamb wave mode velocity can also be changed by a thin film coating on the wafer surface[6]. Fig.2(b) shows the fractional change of velocity along the <100> direction when a 1μm aluminum film is deposited on a 0.5mm thick wafer. The dual effects of film thickness and temperature on the Lamb wave velocity enables us to measure both parameters simultaneously during processing. We employ a time of flight (TOF) measurement technique to measure the time for the Lamb wave to travel from the transmitter to the receiver[6]. Since the distance between the transmitter and the receiver does not change during measurement, we can directly relate the TOF variation to temperature and film thickness change. Theoretical calculation indicates that the TOF changes linearly with temperature and film thickness in a very wide range[6], therefore, we can express the TOF change as

$$\Delta TOF = k_t T + k_z Z$$

where T and Z denote temperature and film thickness change, respectively, and k_t, k_z are the constant coefficients, which can be obtained with experimental calibration. In order to resolve two unknowns -- temperature and film thickness, we use two sets of transmitters and receivers to operate at different frequencies. We note from Fig.2(a) that the temperature coefficient of Lamb waves does not change much with frequency, while from Fig.2(b), we see that the aluminum film coefficient becomes negligible at around 1.6MHz. This implies that if we select one of the transducer pairs to operate at 1.6MHz, the corresponding TOF will not depend on the film thickness but only depend on temperature. In reality, because the transducer has finite bandwidth, the TOF will be affected slightly by film thickness. We express the TOF change as follows:

$$\Delta TOF_h = k_{th} T + k_{zh} Z$$
$$\Delta TOF_l = k_{tl} T + k_{zl} Z$$

where subscript h and l denotes high and low frequency channels. While we choose the two frequencies of operation in the experiment, 0.5 MHz and 1.5 MHz, the coefficient matrix is well conditioned because k_z's change significantly from 0.5MHz to 1.5MHz, and k_t's are not strong functions of frequency. We can therefore obtain the values of temperature and film thickness with a simply linear inversion:

$$\begin{bmatrix} T \\ Z \end{bmatrix} = \begin{bmatrix} k_{th} & k_{zh} \\ k_{tl} & k_{zl} \end{bmatrix}^{-1} \begin{bmatrix} \Delta TOF_h \\ \Delta TOF_l \end{bmatrix}.$$

EXPERIMENTAL SETUP AND MEASUREMENT RESULTS

The experimental setup is shown in Fig. 3. The Lamb waves are excited using a piezoelectric transducer bonded to a 5 cm long fused quartz rod. The tip of the quartz rod is rounded with a radius of curvature of 100μm. 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. An identical transducer/quartz pin set is used as a receiver to detect the Lamb wave transmitted through the substrate. Lead Zirconium Titanate (PZT-5H) is used as the transducer material and the resonant frequency chosen to be 0.5MHz for one transmitter/receiver set and 1.5MHz for the other. The TOF technique employed here is the same as that can be find in Ref 6. Because silicon is an anisotropic material, we use the wafer flat as the orientation reference to align the two transmitter/receiver sets perpendicular to each other along <100> and <010> direction in order to have the Lamb waves travel effectively on the same crystal axis due to the four fold symmetry on (100) surface. The transducers are protected by vacuum tight metal housings so that the PZT is not exposed to the sputtering environment. The accuracy of the temperature and film thickness measurements is mainly determined by the signal to noise ratio (SNR) of the receiver signal. Special care is taken to separate the signal and chassis grounds to prevent ground noise. An ultra-low noise (2μVolts/√Hz) preamplifier is used immediately after the receiver and the signal is amplified by 30dB before it travels out of the sputtering chamber. We have obtained 72dB of SNR in the 0.5MHz channel and 57dB in the 1.5MHz channel.

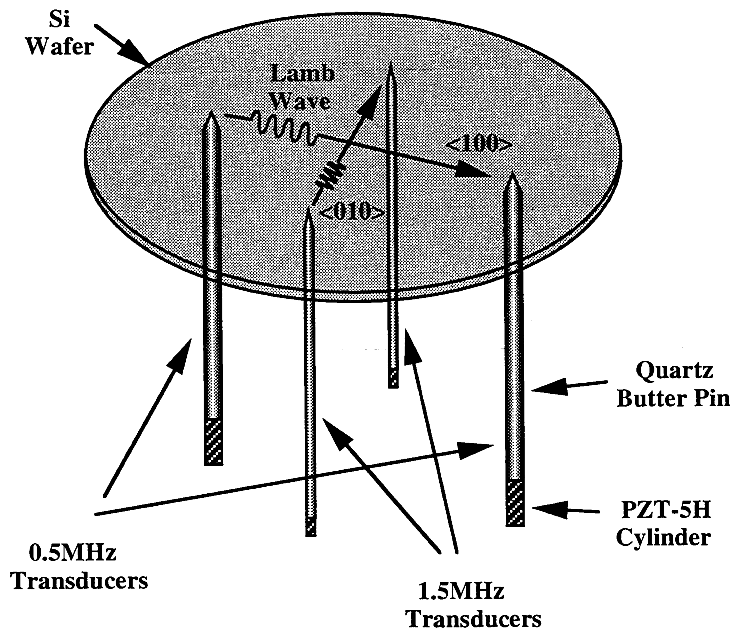


Fig. 3. Experimental setup of the sensor system. Two transmitter/receiver sets are aligned perpendicular to each other along <100> and <010> direction in order to have the Lamb waves travel effectively on the same crystal axis. The quartz buffer pins are 50mm long with diameters of 3mm for the 0.5MHz transducers and 1mm for the 1.5MHz transducers. The sensors are installed in an IBM aluminum sputtering station in which the experiment is performed.

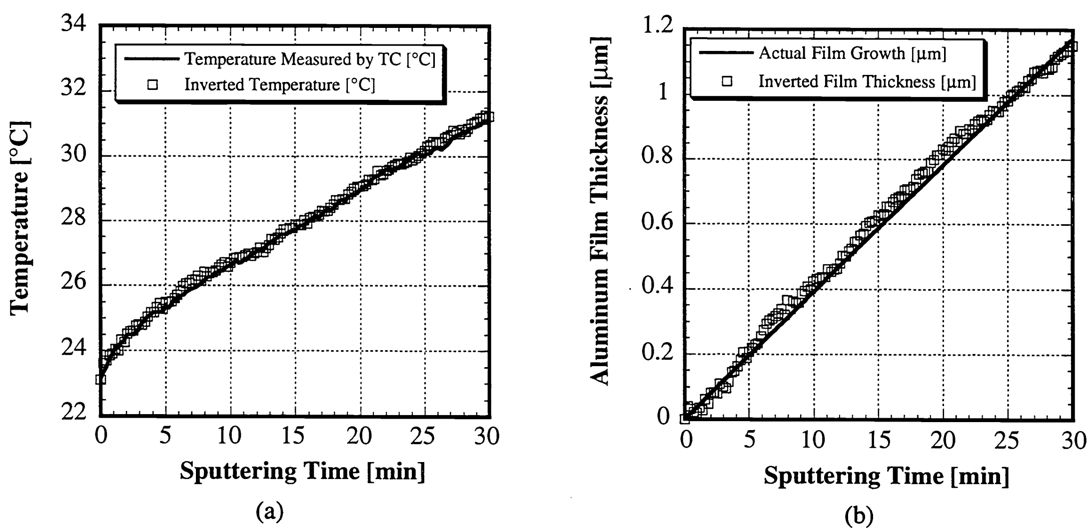


Fig. 4. Simultaneous measurement of temperature and film thickness during an aluminum sputtering process in which about 1.2μm of film is deposited in 30 minutes. During the deposition, the wafer temperature is raised by about 8°C. (a) Temperature obtained using linear inversion compared with that measured by a thermocouple. There is very good agreement between the two measurements. (b) Linearly inverted aluminum film thickness during processing. The sputtering station provides a linear growth rate of aluminum film. The final thickness is measured by a profilometer and the straight line represents the actual film growth. Again, there is very good agreement.

The acoustic sensor system is implemented in an aluminum sputtering system. The aluminum deposition rate is calibrated and chosen to be 400Å/min. During sputtering, a thermocouple is bonded to the wafer and used as a temperature reference. A calibration run is done first with temperature measured by the thermocouple and the film thickness measured by a profilometer. The TOF data during the calibration run is then used to obtain the inversion coefficient matrix which is used for subsequent deposition runs. Fig. 4 describes a typical 30-minute sputtering on a 0.5mm thick silicon wafer during which about 1.2μm of aluminum film is deposited. The TOF data from both the 0.5MHz and 1.5MHz channel are recorded, and the linear inversion is performed to obtain the temperature and thickness during the sputtering run. Fig. 4(a) shows the temperature obtained with our linear inversion from the two channel TOF measurement compared with thermocouple reading. A measurement accuracy of ±0.15°C is achieved. Fig. 4(b) shows the inverted aluminum film thickness during the same 30-minute sputtering deposition, and film thickness resolution is ±170Å.

CONCLUSIONS

Precise control of processing temperature and film thickness is becoming increasingly important in current semiconductor industry, and *in situ* sensors are essential elements in performing the closed loop control of manufacturing processes. We have demonstrated a novel technique for *in situ* simultaneous measurement of both parameters using ultrasonic waves. The acoustic sensor system can be easily implemented into existing industrial processing equipment. The low thermal conductivity of the quartz pins insures 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 silicon wafer or the deposition material. With proper calibration, the sensor can also be used in real-time film property characterization and multi-layer deposition process control.

REFERENCES

1. Y.J.Lee, F.L. Degertekin, J. Pei, B.T. Khuri-Yakub and K.C. Saraswat, Proceedings of IEEE International Electron Devices Meeting. Held: Washington, DC. p.187-190, 1993.
2. Y.J. Lee, B.T. Khuri-Yakub, and K.C. Saraswat, Review of Scientific Instruments vol.65, no.4, pt. 1, p.974-976, 1994.
3. I.A. Victorov, *Rayleigh and Lamb Waves, Physical Theory and Applications* (Plenum, New York , 1967).
6. F.L.Degertekin and B.T. Khuri-Yakub, Appl. Phys. Lett. vol.69, no.2, p.146-8, 1996
5. H.J. McSkimin, J. Acsoutic. Soc. Am, vol.24, p.988-997, 1953
7. J. Pei., F.L. Degertekin, B.T. Khuri-Yakub and K.C. Saraswat, Appl. Phys. Lett. vol.66 no.17, p2177-9, 1995