In-situ film thickness measurements using acoustic techniques

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ABSTRACT

Process monitoring and control of semiconductor fabrication parameters, like film thickness, are important issues, limited at the present time by a lack of adequate sensors. In this paper, we outline the limitations of current film thickness technology and propose two new methods for nondestructive, *in-situ* film thickness process monitoring: acoustic time domain reflectometry (TDR) and acoustic reflection coefficient phase measurements. Theoretical calculations and experimental measurements of different metal films are used to demonstrate the viability of these novel techniques.

2. MOTIVATIONS FOR ACOUSTIC PROCESS MONITORING

Because the fabrication of modern VLSI circuits requires hundreds of steps, process control and monitoring are critical issues in trying to achieve high production yields in a factory environment. Traditionally, statistical process control (SPC), requiring large amounts of empirical data gathering and analysis, has been used as a means of identifying and solving fabrication problems. Due to the slow, expensive nature of SPC, there is a great need to develop process monitoring instrumentation and sensors which provide fast, real-time feedback for key parameters like film thickness.

At the present time, film thickness measurements are made by one of several commercially available instruments, such as an ellipsometer, a surface profilometer, or a quartz crystal oscillator. Although each instrument has certain benefits, they impose several important limitations on film thickness measurement capabilities. The ellipsometer offers a noninvasive means for measuring transparent films, but is not useful for opaque films. The surface profilometer offers good resolution (±100 Å) and the ability to measure opaque films, but unfortunately requires the etching of a film step. This drawback limits its use as a post-deposition process monitor. Quartz crystal oscillators can make in-situ measurements of film thickness, but they only offer an indirect measure of film thickness and cannot measure the film thickness at the point of interest, the wafer surface.

In order to overcome these limitations, acoustic TDR and acoustic reflection coefficient phase measurements have been developed as novel techniques for film thickness measurement. Acoustic TDR offers the ability to make on-wafer measurements of opaque films deposited on silicon wafers without the need for etching a film step. Because of this, it holds a great deal of promise as a post-deposition process monitor where the sample can be scanned under the sensor to generate a thickness map of a thin film. Acoustic reflection coefficient phase measurements also allow on-wafer, opaque film thickness measurements with the added benefit that the measurement can be made from the back side of a silicon wafer instead of from the front side where the film has been deposited. Due to this back side probing, we are presently trying to implement this system inside a vacuum deposition chamber to provide *in-situ* film thickness monitoring.

3. THEORETICAL DESCRIPTION OF TECHNIQUES

The basic schematic for acoustic TDR is shown in Fig. 1 and consists of a standard pulse-echo set-up in which a short, longitudinal acoustic pulse is generated by a ZnO transducer (XD), and the reflected echoes from the sapphire (Al_2O_3)-metal and metal-Si interfaces are analyzed. The thickness X of the metal film is determined by measuring the time separation Δt between the reflected pulses and using the relation $X = 1/2\ (V_o\ \Delta t)$, where V_o is the acoustic propagation velocity in the metal film. In this set-up, the sapphire (Al_2O_3) buffer rod and metal film form a Hertzian contact with a 100-200 μm diameter and a contact force of $\approx 1N$. The short acoustic pulse in the time domain can also be viewed as broadband excitation in the frequency domain. As a result of this broadband acoustic excitation, the interference pattern from the sapphire-metal film-Si system can be seen. To analyze this interference pattern more quantitatively, the acoustic system can be modeled as a multilayered medium whose reflection coefficient vs. frequency can be calculated using transmission line theory. In this multilayer model, both the silicon wafer and the sapphire buffer rod are regarded as semi-infinite media, since their thickness is much greater than the metal film. A typical frequency domain interference pattern for a 2.1 μm gold film is shown in Fig. 2, and can be used to determine the film thickness X by measuring the frequency spacings Δf between maxima (or minima) and using the relation $X = V_o/2\ \Delta f$. In both the time and frequency domains, accurate knowledge of the acoustic velocity V_o is essential for an accurate film thickness measurement.

In acoustic reflection coefficient phase measurements, the same basic schematic as in Fig. 1 is used, except the contact is made from the back side of the wafer and there is no contact with the metal film to be measured. This system is designed for measuring films that are much thinner than the wavelength of the acoustic wave. The thickness of a metal film is determined by measuring the phase of the reflection coefficient from the Si-metal-air interfaces and by comparing the measured phase with theoretically expected results for the same system. The same type of multilayer model is used as in acoustic TDR, with the air and silicon acting as semi-infinite media. Figure 3 shows a typical phase vs. thickness profile for gold films deposited on a silicon substrate. For this measurement, accurate knowledge

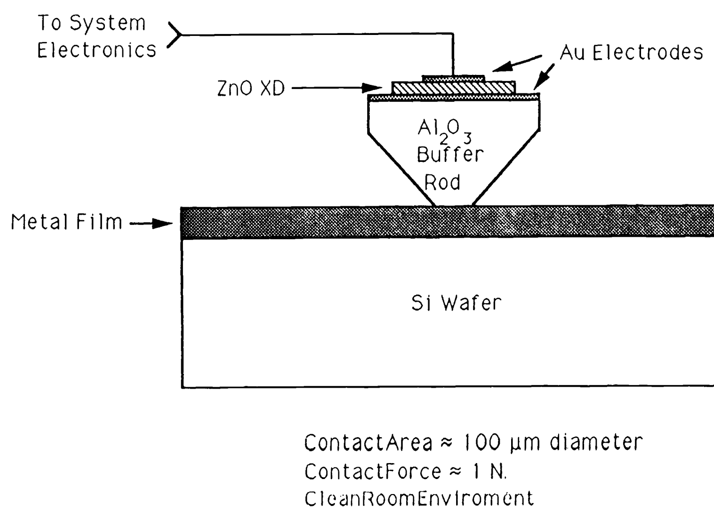

Fig. 1. Basic schematic diagram of acoustic TDR .

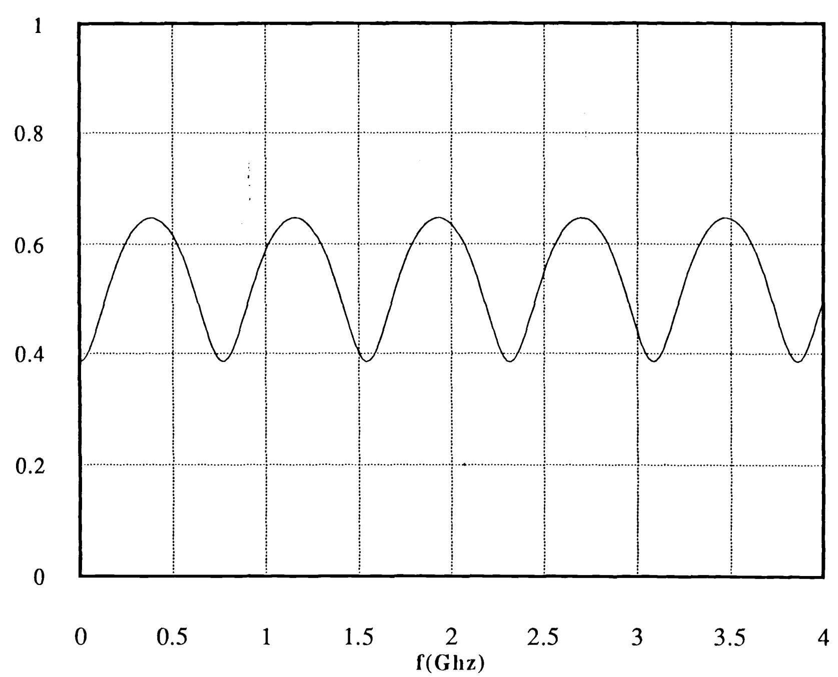

Fig. 2. Theoretical plot of reflection coefficient amplitude vs. frequency for 2.1 μm gold film.

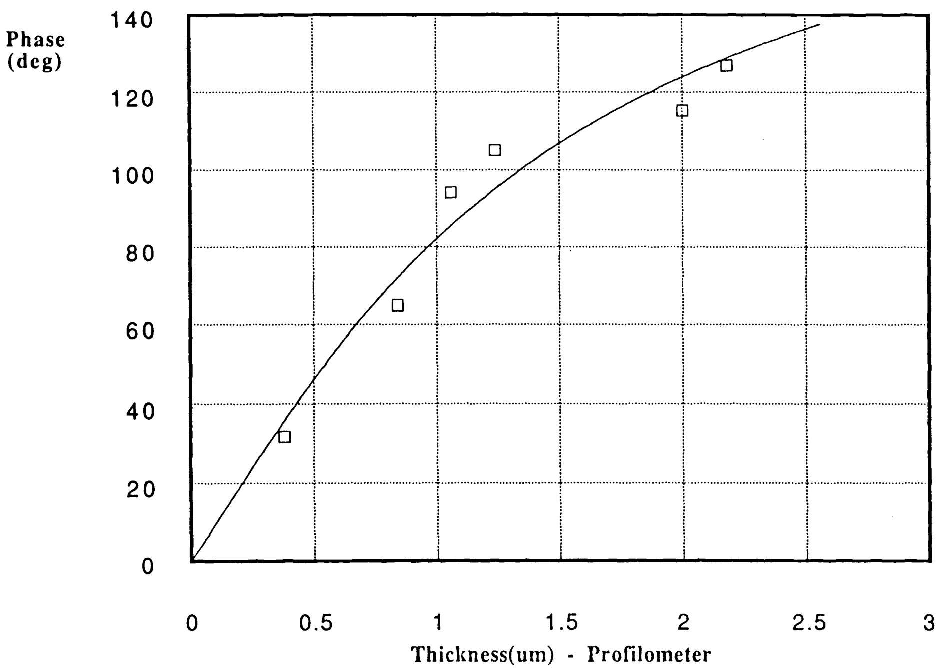

Fig. 3. Theoretical plot and experimental data of phase angle vs. film thickness for gold film. Acoustic propagation velocity V_o and the acoustic impedances of silicon and the metal film are required for an accurate film thickness measurement.

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4. EXPERIMENTAL SYSTEMS AND RESULTS

In the acoustic TDR measurement system of Fig. 4, a 1 μm thick ZnO XD is excited at a 100 kHz rate with a 5 V , 200 psec rise time step generated by a step-recovery diode (SRD) and a slow step generator. The reflected signal r(t) from the acoustic system is sampled by a 10:1 probe and stored and averaged on a sampling oscilloscope. The averaged trace from the scope is then sent to a computer for digital signal processing. Ideally, the SRD electrical step would be converted to an acoustic step by the ZnO XD. However, due to the ZnO XD's finite bandwidth of 3.0 GHz , the fast electrical step excites the step response s(t) of the ZnO XD. Thus, the reflected signal r(t) seen on the sampling scope display is the convolution of the film response x(t) with s(t) . In order to extract the film thickness information, the reflected signal $r(t) = s(t) * x(t)$ is transformed into the frequency domain with an FFT; it is then Wiener filtered by $W(f) = S^*/ |S|^2 + N^2$, where N is the system noise level. The Wiener filter effectively removes the ZnO XD's spectral response S(f) from the reflected spectra $R(f) = S(f)X(f)$, and the final processed signal is thus the interference pattern X(f) from the film-Si wafer acoustic interferometer. The film thickness resolution obtainable from X(f) is

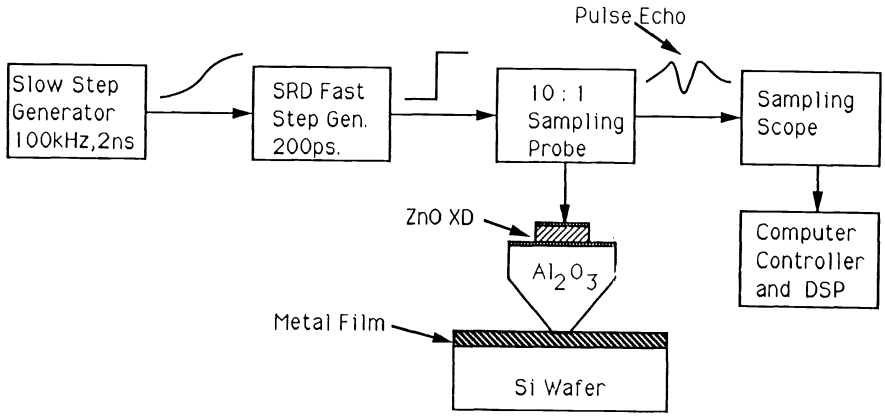

Fig. 4. Block diagram of acoustic TDR measurement system.

set by the ZnO XD's bandwidth and acoustic propagation velocity in the metal film. For gold, the theoretical thickness resolution should be on the order of 0.1 μm .

In order to test the acoustic TDR principle, we deposited gold films on silicon wafers and measured the thickness of the films using both acoustic TDR and a surface profilometer. Figure 5 shows typical time domain data observed on the sampling oscilloscope screen for a gold film. The trace has been averaged 100 times and the time separation between reflected pulses is 1.3 nsec , which corresponds to a 2.1 μm film. From surface profilometer measurements, we also obtained a film thickness of 2.1 μm . Figure 6 shows the frequency domain interference pattern from the same film. An average Δf for this film is 750 MHz , which corresponds to a film thickness of 2.16 μm and a 3 % error with the surface profilometer measurement. Using similar types of frequency domain analyses, we have measured gold films as thin as 0.80 μm with the same types of accuracy.

In the acoustic reflection coefficient phase measurement system, we used an amplitude and phase acoustic microscope capable of operating in the 1-200 MHz range with a phase resolution of

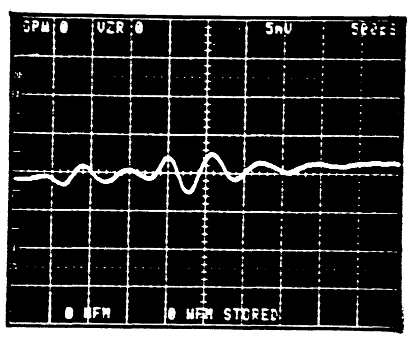

Fig. 5. Typical time domain data for reflected echoes from 2.1 μm gold film.

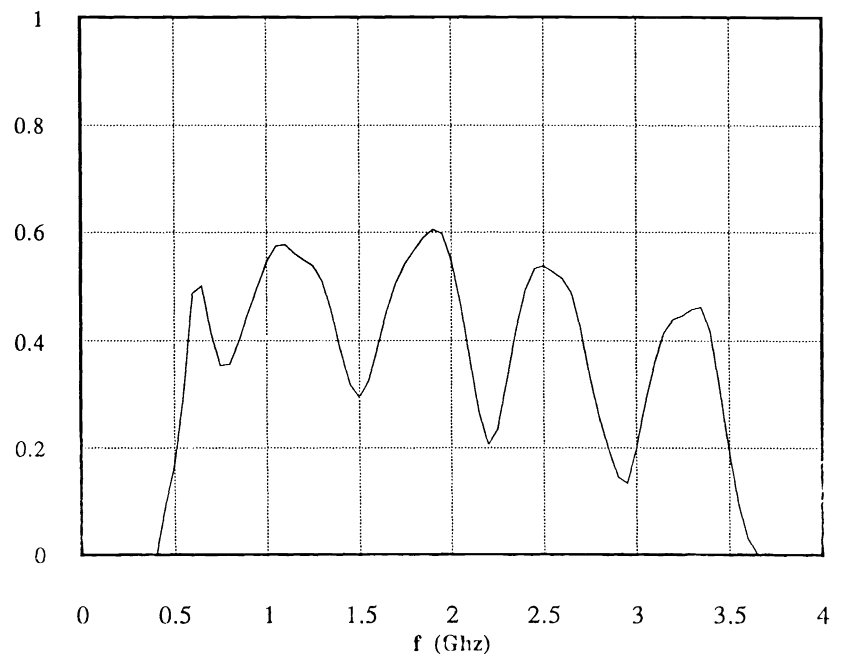

Fig. 6. Experimental data of reflection coefficient amplitude vs. frequency for 2.1 μm gold film.

0.1°. The system uses a 20 μm thick $LiNbO_3$ transducer on a quartz buffer rod, is operated at a frequency of 135 MHz, and is used to contact the backside of double-sided polished silicon wafers which have metal films deposited on their front sides. Since phase measurements are always relative, two measurements were made on each wafer, one measurement where there was a metal film on the front side and another where there was just bare silicon. These two measurements were then subtracted to obtain a final value of the phase for the metal film. Figures 3 and 7 show the results of these measurements for aluminum and gold samples in the range of 0.4-2.4 μm. The errors in these measurements are within 10° of theoretical predictions, which are quite high given the 0.1° phase resolution of the system. The source of these errors is the fact that the silicon wafer thickness varied at the two points where phase measurements were made, and caused a phase error proportional to the thickness variation to appear in the final phase value. Surface profilometer measurements were made on the silicon wafers and showed variations of approximately 1 μm, which corresponds to a phase error of 12°. This error should not appear in the final implementation of the system inside a vacuum chamber since the measurement will be done at a single point and the phase variation versus deposition time will be monitored to determine film thickness. Film thickness measurements with a resolution of 0.01 μm should be possible with this system.

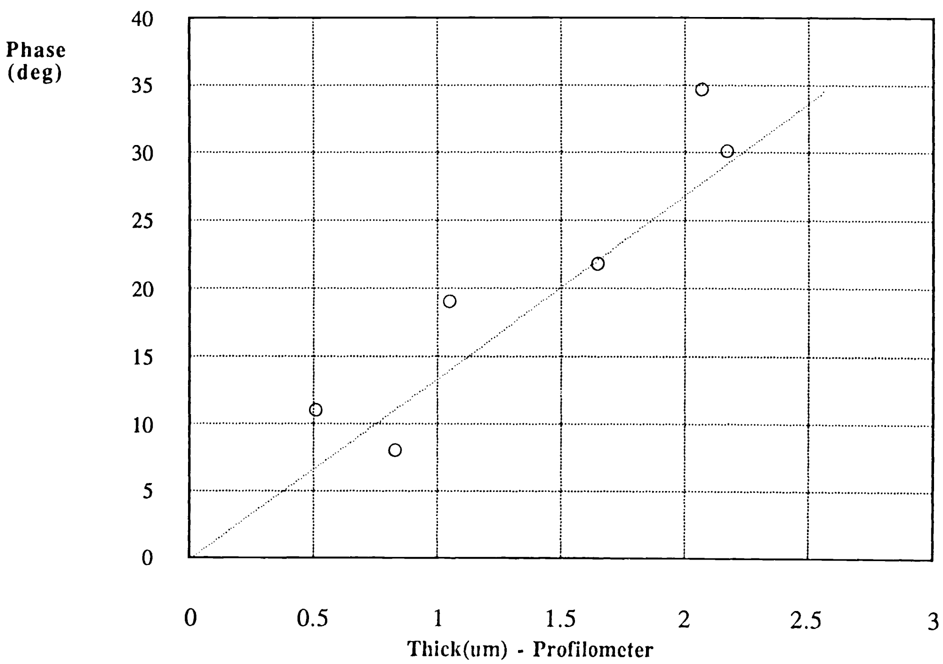

Fig. 7. Theoretical plot and experimental data of phase angle vs. film thickness for aluminum film.

5. CONCLUSION

Theoretical principles and experimental results for on-wafer opaque film measurement systems based on acoustic TDR and acoustic reflection coefficient phase measurements have been presented. An experimental system has been built and preliminary results on gold films show promise for using acoustic TDR as a post-deposition process monitor. Future work should include testing other types of films and improving thickness resolution through the use of a wider bandwidth ZnO XD. Another experimental system based on acoustic reflection coefficient phase measurements has also been built and shows good preliminary results on gold and aluminum films. At the present time, this system is being implemented inside a vacuum chamber to provide *in-situ*, real-time monitoring of film thicknesses. Finally, work is also being done on a photoacoustic technique capable of providing *in-situ* , noncontacting film thickness measurements through the use of laser generated ultrasound.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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