Ultrasonic Monitoring of Photoresist Prebake Using TOF Measurement

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Abstract - We have measured the time of flight (TOF) through a 4" silicon wafer with and without a 1.8μm coating of Shipley 1813 positive photoresist. The TOF change from bare to coated wafer was measured three times on a single wafer; the average of the three experiments was a TOF of 14.3ns (+/-2.5ns), consistent with the calculated expected results. In order to increase the precision of the TOF measurement to the level needed for prebake monitoring, we have applied a least squares algorithm to estimate the transfer function between the echo and received waveforms. Results of pulsed data studies indicate that we can get a decrease in the standard deviation of the TOF measurement from 2.93ns to 2.53ns by determining the TOF from the estimated transfer function.

INTRODUCTION

In current I-line and deep-UV lithography, in situ monitoring of photoresist processing is not required to meet design objectives. However, as feature size surpasses sub-quarter micron, it is expected that the resist materials will be more sensitive to processing conditions such as prebake and postbake time and temperature. It is necessary to prebake photoresist prior to lithographic exposure so that the solvent initially added to decrease resist viscosity can be evaporated, and the resin polymer chains can relax into an ordered array. If the solvent isn't fully evaporated or if the prebake time is too long, then the feature size may not be as small as expected.

There has been some research in endpoint detection of the prebake process. Metz, et al. (1991) performed real-time measurement of resist film thickness on silicon wafers using multi-wavelength reflection interferometry. They determined resist thickness versus spin and bake time. This method was used to monitor non-uniformities for statistical process control. In 1992, Metz, et al. reported on similar experiments with real-time photoresist monitoring to optimize the bake time and spin speed.

At the Edward L. Ginzton Laboratory, several authors have applied ultrasonic technology to monitoring semiconductor processes. Lee, et al. (1993, 1996) developed an ultrasonic technique in order to measure temperature during rapid thermal processing. Lamb waves were excited in the wafer, and the change in wave velocity was monitored as the wafer temperature varied. The wave velocity decreased linearly as temperature increased. In related work, Degertekin, et al. (1993, 1994) applied ultrasonic thermometry to measure the effect of thin films on this ultrasonic measurement of wafer temperature. This technology will be useful in monitoring resist prebake since the wafer temperature and resist film thickness will change as the wafer is heated and the solvent evaporates.

METHOD

First, we conducted experiments in order to characterize the wave velocity in the coated and prebaked wafer. Then we identified continuous-time transfer functions that described the relationship between the echo and received acoustic signals. The transfer function was used to calculate an estimated TOF that was expected to be more precise than the current zero crossing technique for determining TOF.

Resist Characterization By Time of Flight Measurement

In order to characterize the effect of a thin film of photoresist on Lamb wave propagation velocity in silicon, we measured the TOF change before and after the wafer was coated with resist. The method for TOF measurement was described previously by Lee, et al. (1996). Briefly, Lamb waves were excited in a silicon wafer by a quartz pin piezoelectric transducer and detected by an identical transducer. The TOF was determined by the time difference between a chosen zero crossing in the echo waveform reflected from the pin/wafer interface and the received waveform that propagates through the wafer to the second transducer. A Stanford Research Systems SR620 Universal Time Interval Counter was used to measure the time difference between the two zero crossings.

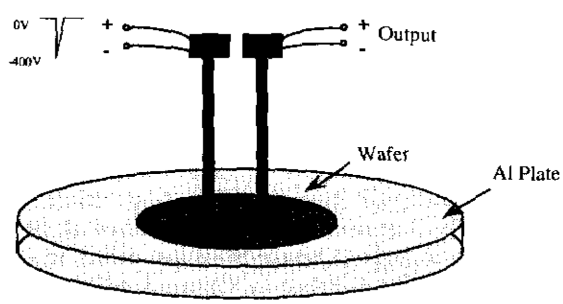

Figure 1: Experimental setup with two quartz transducer pins contacting a 4" wafer placed on an aluminum plate.

The wave propagation velocity can then be determined from the TOF and the spacing between the pins.

For these experiments, 200kHz transducers were fabricated by epoxy bonding a cylinder of 5H PZT, 5mm in height and 3mm in diameter, to a 4" long quartz pin 3mm in diameter. The tip of the quartz pins were cut to a radius of curvature of 10cm to provide good contact for high signal transmission without the problem of multiple contact sites. The pin was designed to be 4" long so that there would be at least 5 cycles of 200kHz signal before reflections from the pin/wafer contact would be seen.

The experimental setup is shown in Figure 1. A 4" silicon wafer <100> doped with boron to a resistivity of 8-12 ohm-cm was placed on an aluminum plate and contacted from above by the two transducers. A voltage pulse (-400V) was applied to the transmitting transducer and the echo and received signals monitored. The TOF was then determined using the zero crossing method; measurements were taken with the transducers raised and lowered between each data point. The wafer was then coated with 1.8μm of Shipley 1813 photoresist to a planarity of +/- 50Å along the signal path. After the wafer was prebaked, it was transferred from the cleanroom to the measurement setup in a dark container to prevent exposure. The resist side was placed down onto the aluminum plate with the pins contacting the opposite side. Double-side polished wafers were used to maintain a reproducible contact. The measurement was repeated and the delta TOF from bare wafer to resist-coated wafer calculated. The wafer was then stripped of resist and the experiment repeated two more times. Results were compared with expected results calculated from theory. Wafer thickness was measured using a Leitz height gauge with 100mm range and 1μm accuracy. Thickness was measured at 5 locations along the propagation path and averaged.

The goal of these measurements is to determine the change in TOF through a wafer with and without resist; expected values are in the range of 12-14ns, depending on the wafer thickness.

Transfer Function Estimation

Our goal is to measure the change in TOF as the resist changes from a liquid to solid during prebake. The expected change in TOF for this 90 second process is -2ns, much lower than the change from bare wafer to resist above. The 2ns includes changes in resist thickness and changes in the elastic properties of the resist. A TOF resolution of less than 0.1nsec will be required to distinguish this change.

In order to increase the precision of the TOF measurement, we have developed a Least Squares fit to a continuous-time transfer function model of the relationship between the echo and received signals. A set of sample signals to be modeled are shown in Figures 2 and 3. The echo signal in Figure 2 will be the model input, $u(t)$, and the received signal in Figure 3 will be the model output, $y(t)$. Data was collected with a at 250MHz 8 bit digitizer. In the time domain, the model is set up as follows:

$$A(p)y(t) = B(p)u(t-\tau) + \varepsilon(t)$$

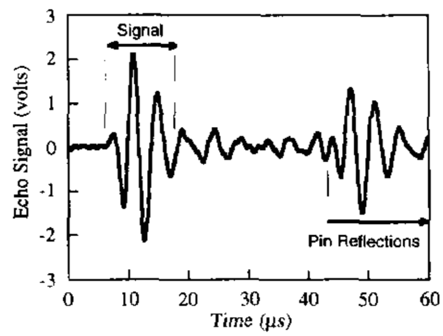

Figure 2: Sample echo signal for modeling

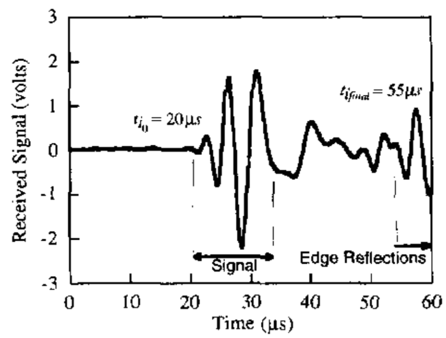

Figure 3: Sample received signal for modeling

where p is the derivative operator, $\varepsilon(t)$ is the residual error and, where:

$$A(p) = p^n + a_1 p^{n-1} + \ldots + a_n$$

$$B(p) = b_0 p^m + b_1 p^{m-1} + \ldots + b_m$$

In the Laplace domain:

$$Y(s) = G(s)e^{-s\tau}U(s) + E(s), \quad \text{where } G(s) = \frac{B(s)}{A(s)}$$

The parameters to be estimated are $a = [a_1 \ldots a_n]^T$, $b = [b_1 \ldots b_n]^T$, and τ. The input and output signals will be filtered with a bandpass filter $G_f(s)$ to give:

$$u_f(t) = G_f(p)u(t)$$

$$y_f(t) = G_f(p)y(t)$$

The filtered equation reads:

$$A(p)y_f(t) = B(p)u_f(t-\tau) + \varepsilon_f(t)$$

and can be rewritten as a linear regression:

$$p^n y_f(t) = \varphi^T(t)\theta + \varepsilon_f(t)$$

where

$$\varphi^T(t) = \left[p^{n-1}y_f(t) \quad \dots \quad y_f(t) \quad p^m u_f(t-\tau) \quad \dots \quad u_f(t-\tau)\right]$$

$$\theta = \left[-a^T \quad b^T\right]$$

For a fixed τ:

$$V(\tau) = \frac{1}{2}\min_{\theta}\sum_{i=i_0}^{i_{final}} \varepsilon_f^{\,2}(t_i)$$

is a least squares problem which can be solved in a straightforward way (Johansson 1993).

The function $V(\tau)$ has several local minima, but it is locally quasi-convex. By evaluating Figures 2 and 3, it is possible to determine in which interval there exists a local minimum that captures the time-delay τ between the echo and received signals. To find the local minimum once the interval is known, a polynomial interpolation method combined with Golden Search techniques was used (Gill et al., 1981). The filtration of the signals was performed in Matlab using a Runge-Kutta ordinary differential equation (ODE) solver. Data points in between those produced by the ODE solver were obtained by linear interpolation. Optimization of τ, a, and b was performed for pulsed transducer excitation signals. The model order used here was $n = m = 4$, and 8000 points were included in the estimation. The number of points was limited to prevent the inclusion of reflections. In Figures 2 and 3, the primary signal and the onset of unwanted reflections from the pin and the wafer edge are identified. The reflections occurring immediately after the signal originate from the pin geometry and are included in the estimation. In Figure 3, t_{i_0} and $t_{i_{final}}$ are the initial and final values used in the estimation. The former was counted from the beginning of the received signal at about 20μs. The final value was chosen based on the point at which edge reflections were seen in the signal. The total number of points in each signal as plotted is 15,000.

RESULTS

Resist Characterization

Figure 4 shows the change in TOF through 4.5cm of a single wafer before and after it was coated with resist. The first ten trials are measurements without resist and the second ten trials were obtained after the wafer was coated with resist and prebaked. Noise of about +/-3ns was measured. An abrupt change in TOF of about 14ns occurred when the 1.8μm film of resist was spun onto the wafer. This value was close to that expected from theoretical calculations (Figure 5) for the 530μm thickness of this wafer.

Figure 5 is a plot of expected change in TOF upon addition of photoresist for different wafer thicknesses. This plot was used to determine the expected value for the 530μm thick wafer. The expected increase can be seen to be about 13.2ns. The average of three experiments on the same 530μm thick wafer was 14.3ns with a variation of +/-2.5ns. Errors from the expected value were within the noise range determined above.

Transfer Function Estimation

Results indicate that the use of transfer function estimation can give an estimate of τ with a standard deviation that is less than that associated with the use of the zero crossing method for determining the TOF. The standard deviation of the τ estimates for 10 sets of echo and received signal waveforms was found to be as low as 2.53ns. This is compared with a value of 2.96ns standard deviation found by applying the zero crossing method to the same waveforms. It should be noted that the values of τ and TOF are not expected to be the same. However, the actual value of the estimated TOF was calculated from separate theory not presented here and resulted in the same standard deviation as that of τ.

CONCLUSIONS

Results of photoresist characterization studies indicate that the measured change in TOF of 14.3ns +/-2.5ns is within measurement noise range of the expected value of about 13.2ns for the 530μm 4" wafer.

Results of transfer function estimation indicate that

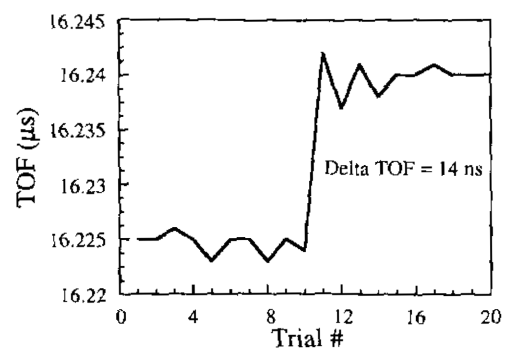

Figure 4: TOF results from single wafer, first 10 trials are without resist, second 10 are after resist has been coated/baked.

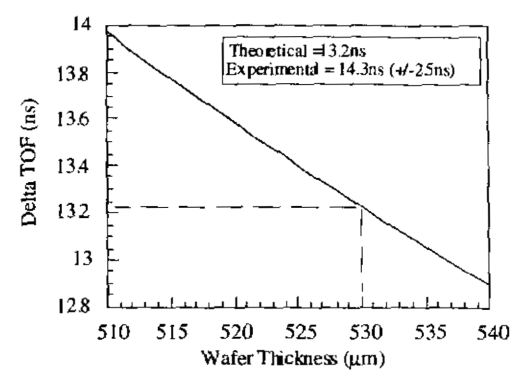

Figure 5: Results of three experiments on same wafer, theoretical and experimental results are shown. Each experimental result is the average of ten measurements.

determining TOF by transfer function estimation can predict the value of TOF with greater precision than when it is determined by the zero crossing technique. The standard deviation was decreased by 14% with the least squares fit estimation. The deviations obtained were for data digitized with an 8 bit digitizer and would be expected to be lower in both cases with an increase in signal to noise ratio. The analog measurement is still more precise (to <0.5ns) but we hope to improve the digitization and signal processing to obtain digital results that are better than the corresponding analog measurements.

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