In-Situ Friction and Pad Topography Measurements During CMP

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Materials Research Society, April 5, 2004

Abstract

Duel Emission Laser Induced Fluorescence (DELIF) and friction measurements are taken in-situ during CMP to observe slurry flow beneath a model of an integrated circuit (IC) wafer. Friction measurements average around 7.5 lb and multiple frequencies are observed. Slurry film thicknesses on the order of a $10 \pm 3 \mu\text{m}$ were observed during CMP of a flat wafer. The film thickness seems uncorrelated to friction measurements except when the pad and wafer rotation speeds are significantly slowed. DELIF has also accurately measured a $9 \mu\text{m}$ etched step, with noise in the image equal to $\pm 3 \mu\text{m}$.

Introduction

Understanding the mechanism behind Chemical Mechanical Planarization (CMP) has become vital to the semiconductor industry as integrated circuit patterning moves from micron-scale to the nano-scale range. CMP is a complicated process due to the number of variables involved [1]; therefore the planarization mechanism is not well understood [2,3]. The research presented here employs a technique called Duel Emission Laser Induced Fluorescence (DELIF) to study slurry transport between the polishing pad and the wafer. DELIF is an optical technique that allows for the measurement of micron scale pad-wafer gap widths to be observed during the polishing process [4,5]. It is able to measure a relative difference to better than a micron. Due to measurement issues, however the absolute distance is only accurate to within $5 \mu\text{m}$. Friction measurements between the pad and wafer are made during this polishing in addition to DELIF measurements [6]. In post processing these data, friction and gap thickness are correlated in time leading to a better understanding of slurry transport and polishing efficiency.

Experimental Setup

Various polishing parameters are adjusted to account for laboratory research scaling and the optical measurements required for DELIF. It is necessary to replace the traditional opaque silicon wafer with a transparent BK-7 glass wafer to enable DELIF measurements. The slurry used during conditioning is a 9:1 water dilution of Cabot Microelectronics' Cab-O-Sperse SC-1 3.1 wt% abrasive. The dilution of the slurry is necessary to maintain a consistent shape of the BK-7 wafer during the polishing run. The

laboratory CMP equipment is scaled down from an industrial CMP system by a factor of 2. A summary of these adjustments are listed in Table 1.

Table 1. Industrial to Laboratory Scaling Adjustments.

<i>Adjustment</i>	<i>Parameter Held Constant</i>	<i>Lab Scale Dimensions</i>
Wafer Diameter	(Pad area)/ (Wafer area)	3"
Pad and Wafer	(Relative Industrial Linear Velocity)/	60 RPM
Rotation Velocity	(Relative Laboratory Linear Velocity)	
Slurry Flow Rate	Flow rate/[(Pad Area)*(wafer position)*(pad rotation velocity)]	50cc/min

Experiments are performed on a Struers RotoPol-31 table top polisher that is integrated with a Mitsubishi Frequl frequency modulator to control pad rotation speed. A Sears 20 inch drill press holds the wafer instead of the standard wafer carrier. The drill press rotation speeds are controlled by a Dayton ½ HP motor. Down force is applied to the wafer using a weighted traverse mounted on top of the drill press. The polishing pad, a Freudenberg flat FX-9, is dyed by the manufacturer to prevent pad fluorescence that may interfere with DELIF measurements. During experimental runs the polishing pad is continuously conditioned using a 163 grit diamond disk to reduce glazing, or smoothing, of the polishing pad [7]. The conditioner rotates as it oscillates radially across the polishing pad. Figure 1 summarizes the experimental setup.

Figure 1. Schematic of experimental setup.

Friction and Thickness Measurements

The Struers RotoPol-31 polisher sits atop a slider force table, which is mounted on a 136 kg solid steel isolation table. The slider force table consists of two parallel plates mounted on either side of a set of linear rails, such that relative motion of the plates is confined to a single tangential direction. Measurements are observed using a force transducer that attaches to both plates. This technique allows for coefficient of friction measurements with uncertainties of ± 0.005 [8].

The DELIF technique is used to instantaneously capture the slurry film thickness during CMP [8]. Two fluorescent dyes, Calciem (Fluorexon) and Coumarin 4 (4-Methyl Umbelliferone), are placed into the slurry, and concentrations are chosen to be 2g/L and 0.125 g/L, respectively. Figure 2 illustrates the optical setup for the experiment. A Quantel Brilliant B Nd:YAG laser emits a pulse at 355 nm. The pulse travels through a beam expander to increase the illumination area of the beam. The beam is then reflected towards the wafer via a fused silica P type mirror.

Once the beam excites the dye in the slurry, the fluorescent light is reflected by a 45° mirror into two 12 bit linear Evolution VF Monochrome CCD cameras. The cameras are mounted at a 90° angle with respect to each other. The light passes through a cubic 50/50 beam splitter. Once the light is split, one beam passes through optical filters that isolate the Calciem emission, while the other beam is passed through filters to isolate the Coumarin 4 emission. Images are acquired at a frequency of 5 Hz, the limiting factor being the maximum frequency of the laser pulses and not the camera acquisition.

Figure 2. Optical setup for dye excitation and emission intensity observations.

Figure 3 illustrates the dye absorbance and emission wavelengths for these experiments. The peak absorbances of Coumarin-4 and Calciem are at 323nm and 492 nm, respectively. The majority of the laser emission should be absorbed by the Coumarin-4 since the absorbance spectrum for Calciem near the laser emission is near 0. The Coumarin-4 reemits the light at longer wavelengths in a region where Calciem absorbs. The energy that is not absorbed by Calciem is filtered and the intensities are recorded by one of the CCD cameras. The Calciem emission intensity due to the Coumarin-4 excitation is filtered and recorded on the second CCD camera.

The ideal one dimensional fluorescence intensity beam from a single dye can be represented by the following equation [9]:

$$I_f = I_e A_f \Phi \epsilon(\lambda) C dl .$$

I_e is the intensity of the excitation, A_f is the fraction of the fluorescent light collected, Φ is the quantum efficiency of the dye, ϵ is the molar absorptivity at the wavelength λ , C is the concentration of the dye and dl is the length across the control volume. Real

fluorescence intensities are sensitive to multiple other factors that include photodegradation and photoquenching of the dyes, chemical changes in the slurry solution, and temperature and excitation energy variations. Most of the affects due to these variables are normalized out of the equation by using a system of two dyes and evaluating the ratio of their excitation intensities [10]. The following equation shows the factors influencing the ratio of the intensities, which is later correlated to a slurry film thickness.

$$\frac{I_{1f}}{I_{2f}} = \frac{\varepsilon_1(\lambda)C_1\Phi_1}{\varepsilon_2(\lambda)C_2\Phi_2}$$

Note that I_e is no longer a variable in this equation meaning that the ratio of the intensities is independent of variations in the laser power.

Figure 3. Coumarin-4 and Calcein absorbance and emission characteristics. Camera filter bands are indicated in yellow.

The fluorescence ratio is correlated to a slurry film thickness by constructing a film of known thickness. Two microscope slides are taped together with double stick tape as illustrated in figure 4a. The thickness of the double stick tape is measured by a Dektak V 200Si Profilometer and determined to be $88\mu\text{m}$. Assuming that the slides are touching on the other side, we can correlate the ratio of the fluorescence intensities to a slurry layer thickness. A fluorescence ratio difference of 0.1 corresponds to approximately $4\pm 1\mu\text{m}$, and $10\mu\text{m}$ corresponds to a ratio of 0.6 ± 0.02 . Figure 4b shows the intensity ratio as a function of distance from the tape.

Figure 4. (a) Calibration Slide Geometry. (b) Fluorescence ratio correlated to slurry film thickness.

Analysis

The friction data presented here are taken during a CMP run using the following parameters. The pad and wafer rotation speeds are set to 60 RPM; the conditioner rotation and oscillation speeds are set to 30 RPM; the slurry flow rate is 50 cc/min; the applied pressure to the wafer is 4 psi. Friction data are taken at a frequency of 1000 Hz. Figure 5a show the force spectrum observed during the 30 second run. The data exhibits multiple high and low frequency sinusoidal signals. Figure 5b shows the power spectrum of this data in frequency space. Frequency spikes at 1Hz and 2Hz and their harmonics can be explained by the experimental parameters for pad, wafer and conditioner rotation speed. However, some of the higher frequency spikes remain unexplained and are likely a result of pad material properties and system of resonance [11].

Figure 5. Friction spectrum and FT analysis.

DELIF images are taken at a frequency of 2Hz during the friction run. Figure 6 shows two images from this run. Most of the images from the experiment are similar to Figure 6a. Linear striations from the top left to the bottom right are probably scratched in the polishing pad due to the diamond grit conditioner. These striations are not observed

as often in newer pad. Both images in figure 6 have dark circular marks, which we attribute to slurry splashing onto the top of the wafer. The 2 large circles in Figure 6a are thought to be a spot of slurry on top of the wafer and its shadow. At some points during CMP the pad/wafer interface is starved or flooded as the slurry waves pass beneath the wafer. Figure 6b is an image of a slurry starved wafer. The black sections in figure 6b are predominantly air bubbles.

Figure 6. Two DELIF images during a polishing run.

From figure 6 and the calibration from figure 4, one can estimate the average distance between the wafer and the pad over this 1/5 of the wafer area. We can then try to correlate this thickness to the friction measured at the same instant. Figures 7a and 7b are first attempts to correlate slurry film thickness with friction measurements. The images collected during DELIF are averaged over the total number of pixels. Each DELIF image correlates to a specific point of the friction spectrum, and the average ratio can be plotted versus the instantaneous friction measurement. After several CMP runs with pad and wafer rotation speeds of 60 RPM, we have not seen any significant correlation between friction and slurry film thickness for either slow or normal rotation rates.

Figure 8 shows a sinusoidal dependence of gap thickness in time when the pad and wafer rotations are slowed to 5RPM. The pattern appears to be periodic, but at frequencies that have no apparent correlation with the system. However, figure 7b shows correlation between the friction and fluid film thickness is observed at 5RPM. More work is in progress to develop a method of matching the “macroscopic” friction observation with the “microscopic” film thickness measurements.

Figure 7. The coefficient of friction at (a) 60 RPM and (b) 5 RPM show no correlation with instantaneous fluid film thickness.

Figure 8. Gap thickness over time during a CMP run with slow pad and wafer rotation.

Wafer/Pad Topography

In addition to studying friction beneath a flat surface, we are using DELIF to study CMP of a patterned surface. We have created a 9 μ m step by HF etching a 2" square glass wafer. The Topography of the wafer is mapped using a Dektak V series profilometer for comparison to DELIF images (figure 9). A static DELIF image of this wafer is shown in Figure 10a. The cross section profile at the yellow line in figure 10a is graphed in figure 10b. There is a clear, although noisy step indicated in the profile. The noise on the step seems somewhat periodic with an oscillation amplitude of approximately 3 μ m. The nature of the noise in this profile has yet to be discovered. The noise could be the actual profile of the pad asperities conforming to the wafer, or the measurements could be close to the limitations of our calibration.

Figure 9. Profilometer map and cross section of a 9 μ m HF etched glass.

Figure 10. DELIF of static etched wafer.

Conclusion

Instantaneous DELIF is used to study the behavior of the slurry film between the polishing pad and IC wafer during CMP. Preliminary results comparing film thickness and instantaneous friction measurements show no correlation at standard CMP operating conditions. There is evidence of a correlation between friction and slurry film thickness at low pad and wafer rotation speed, but more experimentation is required to determine if that relationship is repeatable. DELIF has also been used here to study pad conformation to patterned wafers. A 9 μ m has been detected using DELIF, and the fluorescence ratio difference from the high point to the low point on the step appears to be above the signal noise. FEM modeling efforts are in progress to predict the amount of pad deflection underneath the wafer, and to support observations made during DELIF of patterned wafers.

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