INSTANTANEOUS, HIGH RESOLUTION, IN-SITU IMAGING OF
SLURRY FILM THICKNESS DURING CMP

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Abstract

Dual Emission Laser Induced Fluorescence (DELIF) is used to attain measurements of slurry film thickness during Chemical Mechanical Polishing (CMP). A Nd/Yag UV laser is used in tandem with two 12 bit CCD cameras with a zoom lens to obtain an instantaneous, high spatial and temporal resolution images in-situ. We are able to image individual pad asperities bending under the wafer during polishing. Once the intensities in the images are correlated to slurry layer thickness values, slurry layer roughness is observed. DELIF shows the slurry layer roughness beneath a flat wafer is 4.5±0.5 um. This value compares well to profilometer measurements of pad surface roughness, 4.3±0.3 um. Slurry layer roughness under 27 um deep etched wells in the wafer features is greater than the roughness outside the wells suggesting asperity expansion under features. Slurry layer roughness under air pockets that have accumulated under the wells in the wafer is less than the slurry filled regions under the wafer suggesting incomplete immersion of asperities under the air pockets.
Introduction

Microelectronic devices continue to decrease in size; current features are routinely smaller than 100nm. In addition, many MEMS features now approach the 1-100µm scale (1). These smaller features require smoother surfaces after CMP. As a consequence, the semiconductor industry requires a deeper understanding of the physical processes involved in CMP. Researchers have modeled the behavior of the thin fluid film between the wafer and the polishing pad (2, 3, 4), but it has been difficult to generate physical data to confirm or disprove the modeling results.

For the past ten years, Tufts University has collaborated with the Intel Corporation, Cabot Microelectronics Corporation and the University of Arizona to develop a technique called Dual Emission Laser Induced Fluorescence (DELIF) for the study of Chemical Mechanical Polishing (CMP). We have reported in-situ spatially and temporally averaged measurements of temperature and slurry film thickness (5). Recent modifications made to the DELIF technique have enabled us to view the slurry layer instantaneously during polishing with a resolution high enough to enable viewing of pad features on the asperity level.

Experimental Setup

The polishing setup is depicted in figure 1a. Experiments are performed on a laboratory scale Struers RotoPol-31 table top polisher. The platen carries a 12” diameter polishing pad. The RotoPol polishing head has been replaced by an aluminum shaft driven by a Dayton ½ HP motor that rotates the wafer in the same direction as the platen. The shaft is supported by aluminum beams attached to a steel vibration isolation table. For these data, both the platen and the wafer are rotated at 30 RPM resulting in a pad-wafer relative velocity of 0.34 m/s at the leading edge of the wafer. The polisher sits atop a force transducer table capable of measuring down and shear forces. A (100 grit) diamond conditioner sits atop the polisher table opposite the shaft to prevent pad glazing. Each polishing pad was conditioned for 30 minutes before the polishing run and conditioning continued during image acquisition. A 9:1 dilution of the slurry decreases the removal rate and preserves the shape of the wafer during polishing. The slurry flow rate was held constant at 50 cc/min.

Much of the work reported (6) previously using DELIF to image CMP was done with a UV lamp as the fluorescence excitation source. Here we use a Nd/YAG laser that emits a 1.4W, 6ns UV pulse at 355 nm which provides enough power to image at a maximum sample rate of 10 Hz. For this work, we acquire images at a sample rate of 2 Hz to ensure synchronization of the laser pulse and image acquisition by the cameras. LabVIEW® software provides an interface through which the laser pulses and the cameras can be controlled for slurry film imaging. The cameras were fitted with a Nikon EL-Nikkor zoom lens so that the field of view is approximately 1.6 mm by 2.7 mm.

The DELIF technique is fully presented in previous papers (6, 7, 8), but will be briefly described here. A diagram of the optical setup is presented in Figure 1b. A 3 inch
diameter, ½ inch thick BK-7 optically transparent glass wafer is used to model a silicon wafer. A laser pulse passes through the glass wafer and causes the polishing pads to fluoresce. The slurry was mixed with a fluorescent dye, Calcein, in a concentration of 0.5 g/L. The Calcein in the slurry absorbs the pad fluorescence and in turn fluoresces at a lower energy wavelength. The fluorescence of the pad and the dye are optically separated into two cameras; one observes the pad fluorescence (camera A) while the other detects the Calcein fluorescence (camera B). The ratio, camera B/camera A, eliminates any lighting variations and can be directly correlated to a slurry layer thickness. All images presented here are ratioed, (i.e. no images are individual images from camera A or camera B only).

Figure 1. (a) Polisher Setup. (b) Conditioner, slurry injection and optical setup.

**Calibration and Image Processing**

Once the images are acquired and ratioed, a method is needed to correlate the intensity values, $I$, from the images to a fluid film thickness, $T$. Previous work (5) has proven that the relationship between fluid film thickness and ratio is close to linear. Therefore we should be able to express $T(I)$ as shown in equation 1:

$$T(I) = XI + T(I = 0),$$

where $X$ is the calibration factor. Two glass calibration wafers have been HF etched such that they contain multiple square wells. Figure 2a shows a DELIF image of the wafer containing 14.5 um deep wells, and figure 2b is an image of the wafer containing 27 um deep wells. The darker areas in the image indicate a thinner slurry layer and, hence, a smaller distance between the polishing pad and the wafer. Conversely, brighter section of the image indicates a thicker slurry layer and a larger distance between the pad and the wafer. The average intensities, $I_{14.5}$ and $I_{27}$, under the wells are compared to acquire a relative calibration factor, $X$, as follows:
This calibration factor can be used by itself to compare the thickness at one point in an image to thickness at another point in the image or other images in the run. The factor, $X$, does not directly correlate the intensity values to thickness at a single point in the image. If the intensity of camera B, the camera that detects the Calcein fluorescence, has a value of zero when no Calcein is present, $T(I = 0) = 0$, then this relative calibration would be a valid direct calibration. However, the intensity values of a ratioed image with no Calcein are not zero because the image filters can not filter out 100% of the pad fluorescence. Therefore, $T(I = 0) = -X \cdot I(T = 0)$.

\[ X = \frac{27 - 14.5}{I_{27} - I_{14.5}}. \]  

\[ (2) \]

Figure 2. (a) A 14.5um deep, 0.5mm square well over a Fruedenberg FX-9 polishing pad. (b) A 27 um deep, 0.5 mm square well over a Fruedenberg FX-9 polishing pad.

The results presented in this paper do not require a direct calibration because surface roughness calculations compare single points in an image to a mean thickness value across a subsection of the image. The following section is based upon the assumption that slurry layer conforms to the profile of the pad, meaning we can calculate pad surface roughness from the slurry film thickness data in the ratioed images. For each image, a region of interest is chosen with length, $m$, and width, $n$. All surface roughness values, $R_a$, are calculated from intensity values as follows:

\[ R_a = \frac{\sum_{i=0}^{m} \sum_{j=0}^{n} |I_{i,j} - I|}{m \cdot n} \cdot X. \]  

\[ (3) \]
Results and Discussion

As mentioned earlier, the surface roughness results reported in this paper refer to the shape of the slurry layer and not the shape of the pad. If there are no air pockets between the flat surface of a wafer and the polishing pad, then the slurry fluid is assumed to conform to the shape of the pad surface filling the valleys between asperities. Since the wafer is flat relative to the pad, roughness variations in the fluid layer would correspond to roughness variations in the polishing pad. Note that some of the $R_a$ values presented below will discuss the slurry layer between the pad and the wafer both with and without air pockets.

Profilometer measurements of the Freudenberg FX9 pad used during the runs indicate a pad $R_a = 4.3\pm0.3\,\mu$m. The local $R_a$ values of the slurry layer were measured using DELIF at the region of interest (ROI) depicted in figure 3. Measurements were taken with three different global down-forces applied to the wafer: 0.4, 1.8 and 3.2 psi. All $R_a$ values local to the ROI at these down-forces were within error of each other as shown in figure 3. Comparing DELIF results in figure 3 to the profilometer measurements, we may conclude that over this ROI there is no significant asperity compression. It is our belief that the variations seen in successive DELIF images come from the wafer riding on waves of slurry. The slurry flow to the wafer is not smooth, due to the oscillating pad conditioner. This periodic starving and feeding of the wafer means that at one instant the leading edge of the wafer could be digging into the pad, and the next instant it could be rising up as a slurry wave passes below it. Previous modeling research (ref) has shown that pressure does vary locally beneath a wafer suggesting that we must interrogate many other ROIs before we can draw any significant conclusion about $R_a$ variation with applied global down force.

![Figure 3](image_url)

**Figure 3.** Surface roughness variation with down-force. The region of interest (ROI) interrogated for these data is depicted to the right of the graph.

$R_a$ measurements were made using the calibration wafer with 27 um wells. The solid line in figure 4 is a histogram of the $R_a$ measurements outside the well regions, and the dashed line is a histogram of the $R_a$ measurements inside the well regions. Ra values inside the well seem to be centered at 4.6 um, while outside the well they are centered at 3.7 um. Outside the well regions, the wafer seems to be slightly compressing the pad,
lowering the surface roughness. The asperities are free to expand under the wells and do so. This supports the notion that the CMP polishing regime is of mixed composition. If it were true hydrodynamic lubrication, the roughness under the wells would be the same as the rest of the pad.

**Surface Roughness Inside and Outside Wells**

![Bar chart showing surface roughness](chart.png)

**Figure 4.** Comparison of surface roughness inside and outside the 27um deep wells of the calibration wafer.

The run with the 27 um deep wells contains 200 images. Of those 200 images, 22% show air pockets traveling from the leading to trailing edge of the well. The air accumulates at the trailing edge of the well before dissipating beyond the trailing edge of the well. Figure 5 shows two images with some of the larger air pockets observed.

**Figure 5.** Two images of the 27um deep well over a Fruedenberg FX9 polishing pad.

Figure 6 shows $R_a$ values from the three different regions of DELIF images with air pockets inside the wells. The $R_a$ values of the slurry filled regions both inside and outside the wells mirror the results from figure 4. Average $R_a$ values for regions under
the air pockets are only slightly higher and in most cases are not significantly different than Ra measurements in the slurry filled regions outside the wells. We believe the air pockets are confined to the bottoms of the wells in the wafer with asperities sticking up beyond the fluid coverage within the air pockets. If the air bubbles were shallow enough such that the asperity peaks were fully immersed, then the measured roughness should match other areas under the wells.

![Surface Roughness for Images with Air Pockets](image)

**Figure 6.** Surface roughness inside air pockets compared to slurry filled regions between the pad and wafer.

**Conclusion**

This paper had discussed a method to attain instantaneous, high spatial and temporal resolution images of the slurry layer between the polishing pad and the wafer during Chemical Mechanical Polishing (CMP) using Dual Emission Laser Induced Fluorescence (DELIF). We have examined surface roughness variations in the slurry layer as it conforms to the shape of the polishing pad and wafers. While surface roughness was not observed to vary with global applied down-forces, roughness was observed to vary beneath 27 um deep etched wafer features. Observation of slurry layer roughness beneath air pockets within the wafer features show that the slurry does not completely fill the regions between asperities when air is trapped under the wafer. The data presented here support the idea that a wafer and pad are in partial contact during a CMP polishing run.
References