Characterization of wet pad surface in chemical mechanical polishing (CMP) process with full-field optical coherence tomography (FF-OCT)

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Abstract: Chemical mechanical polishing (CMP) is a key process for global planarization of silicon wafers for semiconductors and AlTiC wafers for magnetic heads. Removal rate of wafer material is directly dependent on the surface roughness of a CMP pad, thus the structure of the pad surface has been evaluated with variable techniques. However, under in situ CMP process, the measurements have been severely limited due to the existence of polishing fluids including the slurry on the pad surface. In here, we newly introduce ultra-high resolution full-field optical coherence tomography (FF-OCT) to investigate the surface of wet pads. With FF-OCT, the wet pad surface could be quantitatively characterized in terms of the polishing pad lifetime, and also be three-dimensionally visualized. We found that reasonable polishing span could be evaluated from the surface roughness measurement and the groove depth measurement made by FF-OCT.

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1. Introduction

Rapid growth of integrated circuit (IC) and hard disk industries has greatly demanded the development of photolithographic patterning process down to tens of nanometers, which in turn, increased the necessity for high level of planarity in wafer surface. Chemical mechanical polishing (CMP) is an alternative process to achieve global planarization of substrate surface [1]. Because of its excellent planarizing capability (a few hundred angstrom), the CMP has been extensively used for ultra-flattening of silicon wafers, metalized layers, interleave dielectrics and copper for circuit interconnects [2–4]. Figure 1 illustrates the basic operation of the CMP process. It is composed of a polishing pad loaded on a rotating table, a wafer carrier, a conditioner, and a slurry feeder. A wafer is mounted at the bottom of the wafer carrier under rotation and pushed down against the rotating pad. Slurry including abrasive particles (~100 nm) is dispensed onto the pad surface, creating chemical reaction with the wafer material and then, the weakened layer is removed by the rotating pad. The rotating conditioner with metallic or diamond grit on it breaks up the surface of the pad, restoring the pad surface roughness which is smoothed due to the polishing work [1].

The planarization performance of the CMP process is mainly influenced by the surface texture of the CMP pad, which directly contacts with the wafer material. Therefore, the pad surface properties such as pad roughness, pad asperity, and pad groove depth play a crucial role in the polishing behaviors including material removal rate and uniformity of polishing [5–8]. For quantitative understanding of the pad surface, many researches have been made with various surface metrology tools like scanning electron microscopy (SEM) [8], stylus profilometry [8], atomic force microscopy (AFM) [9], confocal laser scanning microscopy (CLSM) [10], vertical scanning optical interferometry [2], and laser focused displacement method [11]. Commonly, the previous techniques, however, have severe limitations on in situ pad measurements since the fluidic layer of the polishing slurry on the pad inhibits accurate,
profiling of the pad surface. Thus, the measurements have to be performed only with the dry sample pieces that are cut out from the pad. Of course, the chemical solution and abrasive particles on the pad should be removed carefully for measurement. These destructive approaches are not suitable for providing on-line information about the pad dynamics during use. Recently, an effort to measure the pad in immersion state has been made with ultrasound reflectance technique [12], but the measuring resolution was not sufficient enough to describe the microstructure of the pad surface in detail.

In this paper, we newly introduce the applicability of full-field optical coherence tomography (FF-OCT) for quantitative analysis of the CMP pad surface. FF-OCT is an expansion of high resolution OCT regime, providing three-dimensional (3-D) tomographic images of either bio-specimens or non-live materials [13–18]. The FF-OCT, based on the white light interference microscopy, has been tried even to identify the counterfeit bank notes [19]. By using a pair of identical high numerical aperture (NA) micro-objectives, we can achieve scan-free en-face OCT imaging with high resolutions not only in axial and but also in transverse directions. Further, using immersion-type objective lens enables tomographic imaging even under liquid or wet environment [13–15]. In this work, the feasibility of FF-OCT as an in situ measuring tool of CMP pads is demonstrated. Its efficacy is verified by comparing with conventional analysis tools.

2. Material and methods

2.1 FF-OCT imaging of CMP pad

Details of the FF-OCT set-up used in our experiments are described in [18, 19]. Briefly, bright illumination was provided by spatially incoherent broad-band light (FWHM, 220 nm) from a 100 W tungsten halogen lamp, which was guided to the interferometer via a fiber bundle (7.0 mm diameter). With an iris and a series of lenses, a spatially uniform illumination was made across the field of view. The interference image formed with the beams retro-reflected from the sample arm and the reference arm was projected onto a silicon CCD camera (CCD-1020, 512x512 pixels, 12 bits, 20 fps, VDS Vosskühler) through a 250 mm focal length achromatic doublet lens. A pair of identical microscope objectives (UMPLFL 20XW, 0.5 NA in water, working distance 3.3 mm, Olympus, MO) were used in both arms, and the field of view (FOV) was 670 µm x 670 µm. For obtaining tomographic images of a sample, the four-bucket integrating technique of phase-shifting interferometry (PSI) [13] was utilized, which permitted extraction of an en-face image with acquisition time of 0.2 s. The depth resolution (Z-axis) of the system was measured to be ~0.8 µm in water.

Wafer polishing was carried out with an industrial CMP polisher having proper carrier head pressure and rotating speed. Unfortunately, the CMP polisher was not co-located with the FF-OCT set up. Therefore, instead of in situ measurements, only to see the applicability of FF-OCT to the CMP process, the FF-OCT measurements were made in a laboratory. After polishing, the processed pad was detached from the polisher platen and cleaned with de-ionized (DI) water. Several pad strips, less than a half inch square in size each, were taken from the polished region of the pad and placed into containers filled with diluted slurry. This could build up the in situ environment similar to the thin layer of the slurry on the pad in CMP work. In the sample arm of the OCT, the container was positioned onto a high-precision linear stage having a step resolution of 0.1 µm, and then the front face of the MO was dipped into the medium. A series of en-face OCT tomograms were acquired by axially translating the stage with a step of 0.5 µm, providing depth-resolved contour information of the pad surface. Subsequently, the surface contour of the pad was plotted with a stack of en-face OCT images.

Figures 2(a) and 2(b) show two en-face (XY cut) FF-OCT images of an unpolished new pad at depth of 25 µm and 39 µm below the top surface of the pad, respectively, which were simply excerpted from the stack of 172 en-face OCT images (Media 1). The glaze-like pad asperities and the randomly-distributed circular patterns are clearly visible in its surface and body. From these stack of en-face images, the XZ and YZ cross sectional images could be reconstructed by using commercial 3-D rendering software (Amira, Visage Imaging, Inc.).
2(c) shows the XZ (bottom) and YZ (right) cross sectional images reconstructed along the white lines of a 3-D top view (middle). The cross-sectional images indicate that the pad consists of many asperities (arrows) and pores (asterisks), saying typical features of polyurethane. Movie of XZ cross sectional OCT images makes sure such features (Media 2). Comparison with a scanning electron microscope (SEM) image of the same type new pad in Fig. 2(d) shows that FF-OCT can finely describe the pad surface texture without appreciable signal degradation even under liquid immersion state.

2.2 Pad surface measurement

Figure 3(a) is a cross sectional cut-view image reconstructed from a stack of en-face OCT tomogram images, as Fig. 2(c). The data points (512 points) of the cut-view image were interpolated and smoothed, and curved fitted with a green curve as in Fig. 3(b), which shows the surface contour profile of the pad as Fig. 3(c). From the contour profile, the pad surface could be quantitatively evaluated with several roughness parameters related with the CMP process [6, 8]; the roughness average (Ra) and the maximum roughness depth (Ry). The Ra is
one of the most-effective surface roughness parameters, which is commonly quoted in general manufacturing practice. It is defined as the average of absolute deviation from the height mean value (Rm) as shown in Fig. 3(c). Ry (or Rmax) is the maximum peak to valley profile height, which is adopted to present the pad groove depth in this research. Data set of such parameters is made with the total of 512 cut-view OCT images.

3. Experimental results

The pad surface characterization using the FF-OCT system has been investigated with a new pad and several used pads, which had been suffered from polishing wafers for 68, 139, 178 times, respectively. And the pad at the end of its pad life was also investigated. Likewise, the changes of the pad groove depths were also observed. Generally, pad grooves are periodically patterned on the pad surface to readily transport the polishing slurry into the pores of the pad at the polish site. For each experiment, additionally SEM and commercial Wyko optical profiler measurements (vertical scanning interferometry (VSI) mode, 640 µm × 480 µm FOV (field of view)) were made with dried samples to compare with the FF-OCT measurements. It is noted that the pad samples for these three measurements were different but taken from the same pad. To minimize variation among samples, we have tried to get the samples at adjacent areas of the pad.

![Fig. 3. (a) Cross-sectional cut view (XZ) extracted from 3-D OCT data, (b) Extracted surface profile (green line) of the pad surface, and (c) The surface roughness Ra calculated with the surface profile.](image)

Figure 4 shows top views (XY, pseudo colored) of 3-D rendered pads, their cross sectional (XZ) view (taken along the horizontal white line) OCT images, and the corresponding SEM images taken with the pads having different life time. We can see that in the new pad (unpolished), the pad asperities are mostly related with the initial porosities of the pad surface (Fig. 4(a)). The asperity shapes on the wear pads are still active with 68 wafer polishing (Fig. 4(b)) and 139 wafer polishing (Fig. 4(c)). It is because the conditioning process opens up the
pore cells by cutting the pad surface and regenerates the pad asperities, which maintains consistent pad roughness.

| Pad usage                  | 3-D OCT image of pad surface (Top view) | Cross-sectional OCT image of pad (white line in 3D OCT image) | SEM image (500X) |
|----------------------------|----------------------------------------|-------------------------------------------------------------|-----------------|
| (a) Unpolished new pad    | ![Image](image1.png)                   | ![Image](image2.png)                                       | ![Image](image3.png) |
| (b) 68 wafers polished pad| ![Image](image4.png)                   | ![Image](image5.png)                                       | ![Image](image6.png) |
| (c) 139 wafers polished pad| ![Image](image7.png)                   | ![Image](image8.png)                                       | ![Image](image9.png) |
| (d) 178 wafers polished pad| ![Image](image10.png)                  | ![Image](image11.png)                                      | ![Image](image12.png) |
| (e) End of life pad       | ![Image](image13.png)                  | ![Image](image14.png)                                      | ![Image](image15.png) |

Fig. 4. Experimentally obtained 3-D FF-OCT images, cross-section images, and SEM images (500 × ) taken with; (a) new pad, (b) 68 wafers polished pad, (c) 139 wafers polished pad, (d) 178 wafers polished pad, and (e) life-ended pad. White bars in the cross-sectional OCT images are 20 µm (vertical) and 100 µm (horizontal).

Meanwhile, after 178 wafers processing, the degradation on the pad surface roughness, attributable to the continued polishing and with over-conditioning, clearly appears as in Fig. 4(d), which is similar with the one taken at the end of pad life as shown in Fig. 4(e). From these OCT images, the Ra distribution was calculated with 512 different height profiles of the pad and a single Ra was also obtained over the pad area (512×512 pixels). The resulting data were compared with the ones (area averaged, red circles) taken with the Wyko as in Fig. 5. In Fig. 5, the error bar is the standard error of the line averaged Ra values (black squares). The variation of error bar just means that the distribution of pores and their sizes are not uniform across the pad surface as shown in Fig. 4. We can see that the area averaged Ra of OCT (blue triangles) shows closer agreement with the Wyko’s result than the line averaged Ra. It is interesting that in the area Ra values of the OCT, the Ra value (7.84 µm) at the end of pad life is less than 81% of the Ra value (9.67 µm) of the new pad.
Furthermore, we have measured the pad groove depths with respect to the pad usages. It is worth noting that the cumulative polishing and conditioning induce pad thinning, which reduces the depth of the pad groove. Figure 6(a) shows the 3-D FF-OCT images of the grooved pads and their cross sectional views taken along the white lines. The distributions of the measured pad groove depths (512 Ry values) are co-plotted with the ones obtained with Wyko in Fig. 6(b). The behavior is well agreed to the Wyko’s; the pad groove depth was decreased as pad was used. However, in absolute values the two measurements gave different values. Considering that the $R^2$ value of 0.999 as a correlation coefficient between two measurements, as shown in Fig. 6(c), OCT measurement is highly correlated with commercial Wyko’s. However, there might be a calibration problem in one of the modalities. Note that the pad groove depth at the end of pad life (83.4 µm) is almost down to 81% of the new pad value (439.8 µm).
4. Conclusion

We have introduced a new approach of full-field optical coherence tomography (FF-OCT) for quantitative measurements of pad surfaces under a CMP work. In situ pad surface analysis is imperative for achieving more efficient and productive CMP process, but it has been poorly done for conventional profilers due to presence of slurry layer on the pad. The proposed FF-OCT scheme offered a superior means of overcoming such issue by employing the dipping mode. In addition, the intrinsic FF-OCT feature of a sub-micron spatial resolution allowed the characterization of the pad surface texture even under slurry mixture. We have demonstrated the profiling capability of the FF-OCT with wet pad samples. The roughness of the pad surface was measured with respect to the number of polishing usage, and the same measurements were made for the depth of the pad groove. The OCT measurements clearly showed that the roughness of the pad surface was kept up to 139 wafer polishing and gradually degraded. Whereas, the groove depth was rapidly reduced due to pad wearing of the polishing and conditioning, which implies that these roughness quantities enable to properly control polishing condition in CMP work. We also found that our OCT measurements showed good correlation with commercial Wyko measurements and SEM observations. Further, we expect that the mosaicing of FF-OCT images would display large areas of the wet pad and overcome limited field of view (FOV) of our tomographic microscope, providing more comprehensive understanding of the pad measurements.

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