Proceedings of the STLE/ASME International Joint Tribology Conference
IJTC2007
October 22-24, 2007, San Diego, California, USA

IJTC2007-44488

# THE EFFECT OF MICROSTRUCTURE ON CHEMICAL MECHANICAL POLISHING PROCESS OF THIN-FILM METALS

**Joseph Bonivel, Sarah Biltz, Elon Terrell, Burak Ozdoganlar, and C. Fred Higgs III**
Mechanical Engineering Department
Carnegie Mellon University

## ABSTRACT

Chemical mechanical polishing (CMP) is a critical nanomanufacturing process used to remove or planarize ultra-thin metallic, dielectric, or barrier layers on silicon wafers. The CMP process is a vital interim fabrication step for integrated circuits and data storage devices. One of the major shortcomings of existing CMP models is that they do not account for crystallographic effects of the thin film metal materials when predicting material removal rates. This work investigates the effect of the microstructure on the CMP of copper and metal thin films on silicon wafer. Nanoindentation tests were conducted to measure the hardness variations across a wafer surface due to the crystallography of the metal films. Spatial variation of mechanical properties was also input into an existing multi-scale CMP model. Nano-characterization and CMP experimental results are presented and compared to an existing CMP wear model.

## INTRODUCTION

This paper addresses the influence of the microstructure[1-4], namely crystallographic orientation and associated hardness variation on material removal rate during chemical mechanical polishing (CMP). The CMP process uses an abrasive and corrosive chemical slurry (commonly filled with nanoparticles) in conjunction with a polishing pad and retaining ring. The pad and wafer are pressed together by a dynamic polishing head and the polishing head is rotated with different axes of rotation. This removes material and tends to planarize any irregular topography, making the wafer extremely smooth. The synergistic effect of the abrasives, mechanical polishing, and the chemicals reaction of the slurry produces the polished wafer.

An integral part of the material removal is the mechanical action of the abrasive nanoparticles and the chemical etching of the fluid phase of the slurry. Since CMP includes numerous mechanical interactions, this multi-phase tribological phenomenon is difficult to predict. One major shortcoming of the existing CMP models is that they do not account for the crystallographic effects of the materials into tribological material removal rate (MRR) relations. Tribological MRR models mainly account for the mechanical removal [5, 6] and weakly account for the chemically-induced removal [7, 8] by using the well-known (but rudimentary) Preston Equation (1):

$$MRR = k \cdot \frac{P_{app}(x, y) \cdot U}{H} \quad (1)$$

where $k$ is the Preston wear coefficient which accounts for the chemical and mechanical removal based on polishing experiments, $P_{app}$ is the applied pressure on the wafer, $U$ is the relative velocity between the wafer and platen, $H$ is the hardness of the material being removed, and $MRR$ is the material removal rate (typically in nm/min). Usually, wear equation assume the hardness $H$ is essentially constant throughout the material, which means that the Preston wear coefficient $k$ captures more uncertainty than intended when predicting the material removal or wear.

In this work, an empirical formulation that describes the variation of mechanical properties of a copper wafer arising from the microstructure is derived from the experimental data. This formulation will be input into an existing first-principals CMP model to predict the material removal rate of thin film copper on a wafer substrate.

## NANOMECHANICAL CHARACTERIZATION OF THIN FILMS

The thin film samples were produced by using sputter deposition. The thickness of the deposited copper is 1.5 microns. Orientation imaging microscopy (OIM) is used to determine the pre-processed microstructure. The three-dimensional (3D) surface roughness is obtained before and after CMP using an optical profilometer. Additionally, the pre- and post-CMP grain size and orientation distributions are examined using OIM. This gives insight into the effectiveness of accounting for the spatially varying hardness.

Prior to characterization of the thin metal films, the samples are annealed in an argon gas furnace for a pre-determined amount of time based on in-house optimization studies. The thin metal films are characterized through OIM, which was applied through the Electron Backscatter Diffraction (EBSD) technique in an Scanning Electron Microscope (SEM). The OIM data is collected by moving the electron beam to points on a regular grid, defining an area of interest for the sample. At each point an EBSD pattern is acquired and automatically indexed to obtain the orientation information. The orientation, position of the beam within the grid, and quantitative values for both pattern quality and indexing results are recorded.

The data can be used to form a variety of maps and plots giving insight into the microstructure. OIM is used to visualize the orientation aspects of microstructures and gather statistical information on preferred orientation or texture in the material. A single scan can provide a wealth of very detailed and complex information on material microstructures. The nanomechanical characterization in this work includes determining the hardness of each individual grain determined from OIM. A Hysitron nanoidenter will be used to perform these tests and create a hardness map.

## EXPERIMENTS

All CMP experiments were performed using Strasbaugh 6CA polisher. This is a full scale CMP system in which the pad, 200 mm in diameter, is mounted on a turntable that can be rotated about its center. The material to be polished is copper (Cu) on a silicon (Si) wafer substrate. The wafers were mounted in a holder that can be pressed against the pad by an applied load. The load was varied over a range such that the nominal pressure ranged from 0 to 25 psi. The squares were polished for a variety of time ranging from 15 seconds to 1 minute with intervals of 15 seconds. Polishing parameters of importance include:

| **CMP Parameters** | **Values** |
|---|---|
| Speed of pad | 250 rev/min |
| Angle of arm of CMP | 17 degrees |
| Radial distance to center | 2 cm |
| Speed of wafer (square | 375 rev/min |

## MODEL DEVELOPMENT

In what the authors have named particle augmented mixed lubrication (PAML) based wear, the material removal rate is predominantly due to the asperities and the abrasive particles. In the CMP problem, there is material removal due to the mechanical abrasion from the particle and due to chemical etching. While quite similar to what tribologists call the "wear equation", the "Preston's equation" is the rudimentary and highly empirical MRR equation (1) for CMP. The coefficient $k$ is an all-purpose coefficient determined from polishing experiments that accounts for the unknown chemical and mechanical factors that cause the material removal. Unfortunately, the over-compensating Preston equation (1) neglects numerous CMP factors such as particle properties, chemistry, and microstructure variables. After finding the contact stress σ between the pad/wafer in Eq. (2), the material removal rate $MRR_{asp}$ can be applied locally at the asperity level using Eq. (3).

$$\sigma(x,y) = \frac{E_{asp}}{t_{asp}} K(\nu)\cdot[z_1(x,y) - h(x,y)] \quad (2)$$

$$MRR_{asp}(x,y) = f[\delta_w(H_w{}^*,\cdot D_p\cdot, E_{asp}\cdot,\sigma),\cdot t,\cdot U] \quad (3)$$

## RESULTS AND DISCUSSION

Nanoindentation tests have been conducted to demonstrate the variability of hardness across a wafer surface due to the crystallography of the metal films. Spatially-varying mechanical property data for a wafer specimen are input into an existing multi-scale (i.e., wafer to asperity scale) model for predicting chemical mechanical polishing. Quantitative and qualitative results will be shown.

## CONCLUSION

The results highlight the importance of considering microstructure in performing CMP during the nanofabrication of next-generation semiconductor and data storage devices. The crystallographic effects of the metal layer induce spatial variations of surface quality on wafers processed during CMP. This work will lead to an understanding of the complex multi-physics CMP problem.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Alfred P. Sloan Foundation, Pennsylvania Infrastructure Technology Alliance (PITA), National Science Foundation (NSF), and the NSF MRSEC program for their support of this work.

## REFERENCES


1. S. H. Kang, Y. S. Obeng, M. A. Decker, et al., Journal of Electronic Materials **30**, 1506 (2001).
2. R. K. Maynard, S. J. Pearton, and R. K. Singh, Journal of the Electrochemical Society **149**, 648 (2002).
3. M. Nowell and A. Frank, JOM **56**, 47 (2004).
4. W.-T. Tseng, Y.-L. Wang, and J. Niu, Thin Solid Films **370**, 96 (2000).
5. C. F. Higgs III, S. H. Ng, L. Borucki, et al., Journal of the Electrochemical Society. **152**, 1 (2005).
6. L. Shan, J. Levert, and S. Danyluk, Mat. R. Soc. Symp. Proc. **566**, 187 (2000).
7. J. Luo and D. Dornfeld, IEEE Trans. on Semiconductor Manufacturing **16**, 45 (2003).
8. S. Sundararajan, D. G. Thakurta, D. W. Schwendeman, et al., J. of The Electrochemical Soc. **146**, 761 (1999).