In-Process Detection of Microscratching During CMP Using Acoustic Emission Sensing Technology

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An experimental investigation on the correlation between the microscratches and the signal characteristics of acoustic emission (AE) generated during chemical mechanical planarization (CMP) has been performed. CMP experimental results from both laboratory and production line CMP machines have clearly showed that AE rms voltage in the time domain has distinctive features relating to scratching. The sensitivity of AE signals to the CMP process state change was also investigated. The results show that this AE sensing technology can be used as a tool for in-situ microscratch detection and process monitoring in CMP.

Key words: Acoustic, chemical mechanical planarization (CMP), emission, microscratch, sensor

INTRODUCTION

By micro-electronic fabrication standards, chemical mechanical planarization (CMP) is an inherently dirty process and leaves micro defects, such as residual slurry, particles, pits and microscratches on the polished wafer surface. Some of the defects can be removed by post CMP cleaning. But defects like microscratches, cannot be recovered by simply cleaning the wafer and therefore should be especially addressed for the purpose of increasing chip yields. The microscratch generation mechanisms are not yet clear, but slurry contamination, is most likely to be responsible.

Another scratch source is due to large particles dislodged from the conditioning wheel during pad conditioning. A polishing pad is usually made of a cast and sliced sheet of polyurethane with fillers to provide the necessary porosity. As the polishing process continues, and due to slurry particle build-up and pad erosion in CMP, the pad surface becomes smoother and the pores are filled with particles. This phenomenon is called glazing and can cause the polishing rate to decay.[1,2] Conditioning technologies are usually applied to these glazed pads to remove deformed pad material and open new pores on a pad and maintain required surface roughness for slurry transportation. There are several pad conditioning methods. One of the most practically applied methods is to utilize a diamond wheel to perform this conditioning task. This method has advantages of high conditioning efficiency with easy control of the conditioning parameters. However, a critical shortcoming of this method is that the diamond grit may be pulled out of the conditioning wheel and temporarily remain in between the pad and the wafer. This results in a severe scratch in a wafer and therefore significantly decreases the throughput.

Microscratches can fill with metal and cause puddles and slivers that lead to circuit shorts.[3] Therefore, prediction or early detection of a microscratch is an important research topic from the viewpoint of industry application of CMP technology in integrated circuit (IC) fabrication. This research attempts to address this topic by using acoustic emission sensing technology. Our goal here is to identify the microscratch in CMP based on the information contained in acoustic emission (AE) signals and provide a strategy for microscratch prediction.

SCRATCHING CRITERION

Slurry contamination, such as accumulated particles from the slurry abrasives, fragments abraded from the wafer surface and the pad surface, and the

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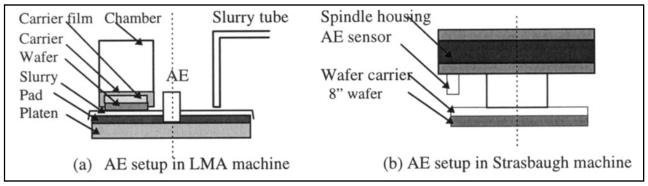
particles from the environment or conditioning wheel, are most likely to be responsible for microscratch occurred on the polished wafer surface. In addition to these scratch sources, process parameters also have significant influence on scratch occurred by affecting slurry film thickness.

In a study of the tribology of the pad-slurry-wafer interface during CMP, Runnels and Eyman[4] identified three types of wafer-pad contact modes: namely (1) direct contact; (2) semidirect contact, and (3) hydrodynamic lubrication contact. In direct or semidirect contact modes, material is likely removed by Hertzian indentation and typical abrasive interaction in which the abrasive particles are dragged across the wafer surface and act as cutting tools. Obviously, a scratch is most likely to occur in these two modes. In hydroplane contact mode, material removal may occur by fluid-based wear, that is, abrasive particles impinging on the surface at some velocity and angle, resulting in weakened bonds and removing materials.[5,6] In fact, two and three body interaction with ductile and brittle behavior is likely to occur under typical CMP conditions. In CMP process, slurry film thickness usually decreases with decreasing velocity and slurry viscosity. Therefore, the contact mode can shift from hydrodynamic lubrication contact mode to semidirect contact mode or even to direct contact mode by changing velocity or viscosity to a lower value.[4,6] In other words, scratches are likely to occur while polishing is operated at some specific condition, such as at a lower velocity or lower slurry viscosity.



(a) AE setup in LMA machine (b) AE setup in Strasbaugh machine

Fig. 1. Schematic of CMP process with AE monitoring.

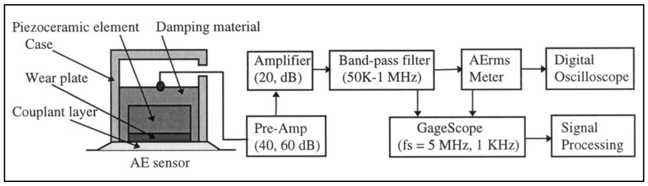


Fig. 2. Instrumentation for AE acquisition and analysis.

THE REQUIREMENT FOR A NEW SENSING TECHNOLOGY FOR CMP PROCESS MONITORING

CMP is a planarization technology suitable for logic and DRAM devices with feature sizes in the subhalf micron range. Through a consistent polishing process, defect free, high material removal rate and acceptable within-die, within-wafer, and wafer-to-wafer uniformity can be achieved. Typically, CMP is used for removing a thickness of dielectric material which has been deposited onto a substrate on which a variety of integrated circuit devices have been formed. As in a conventional CMP process, the material removal rate is usually in the range of 100–800 nm/min in thickness, which is extremely small compared to conventional machining such as grinding or diamond turning. Monitoring the material removal process in CMP planarization is, therefore, a difficult task using traditional sensors such as current, load cell, or strain gages. Fukuroda et al.[7] detected and analyzed the signals of small vibration of the polishing head and related the signals to surface planarization, surface nonuniformity, pad wear, etc. Because the vibration signal is not due directly to the material removal process in CMP, the sensitivity of this method is limited. There have been several additional studies on this subject.[8–11] These techniques, however, are all focused on endpoint detection in CMP process and have some limitations in sensitivity. Therefore, they are not suitable for reliable CMP process monitoring, especially for microscratch detection. The lack of sensitive and robust sensing systems results in an increase in cost of ownership of CMP process and makes the CMP process optimization a challenge.[12]

Acoustic emission refers to elastic waves generated by friction, crack formation/propagation, dislocation motion, phase transformation, or boundary sliding. AE signals generated during manufacturing process has found to be a very sensitive to machining and abrasive process performances, such as tool wear/breakage, chip form changing, ductile/brittle transition in ceramics machining, and material removal rate variation in lapping of brittle materials.[13] It is further proved by numerous other researchers in the field of tribology, that acoustic emission signal features are a very sensitive indicator of the degree and nature of contact between surfaces and will be the basis for the monitoring of the CMP process.

Table I. Experimental Conditions

	LMA CMP Machine	Strasbaugh CMP Machine
Wafer	4″ wafer	8 ″ wafer
Films	Spin-on glass. Thermal oxide	PE-TEOS
Slurry	(1) ILD 1300 (silica based slurry, 140 nm) (2) ILD 1300 + slurry with 1 μm diamond	(1) SC 112 (silica based slurry, 140 nm) (2) SC 112 + slurry with fine Al_2O_3
Pad	IC 1000	IC 1000/Suba IV set
Back pressure	0.15 PSI	8 PSI
Platen speed	6 rpm	65 rpm
Carrier speed		25 rpm

CMP EXPERIMENTAL SETUP

Experiments were conducted at the Laboratory for Manufacturing Automation (LMA) and Advanced Micro Devices Inc. (AMD) using both laboratory CMP machine (LMA machine) and Strasbaugh production line CMP machine. On the LMA machine, the AE sensor is fixed to the center of the polishing platen which is stationary during polishing, see Fig. 1a. On the Strasbaugh machine, the AE sensor is attached to the spindle housing as shown in Fig. 1b. The instruments for signal acquisition and analysis are shown in Fig. 2. The raw AE signal was fed through a preamplifier with fixed 60 dB gain and built-in high-pass filter with 50 KHz corner frequency. This output was further amplified by a Dunegan amplifier with 20 dB gain and fed to an AE rms meter with averaging time of 8 ms. Both the AE raw and AE rms signal are digitized on-line through an A/D channel of the data acquisition board with commercial GageScope software on an IBM PC-AT for further analysis.

All experiments used unpatterned wafers. The experimental conditions are listed in Table I. CMP operation was programmed using existing software which can easily set up or adjust operation parameters, such as back pressure, slurry flow rate, carrier speed. The conditioning was performed using a motor driven conditioning unit installed on a Strasbaugh CMP machine and applied after each wafer was polished. Conditioning was also programmed with existing software which can control the downforce applied to the conditioning wheel, control the conditioning time, the speed of the conditioning wheel, and the speed of the polishing platen.

EXPERIMENTAL RESULTS AND DISCUSSION

AE Sensitivity to the Fundamental CMP Parameters and Process Stability

The CMP process factors such as polishing load, wafer carrier rotation, platen rotation speed, and back pressure have significant effects on the dielectric material removal rate and planarization. Both material removal rate and planarization characteristics are critical issues in CMP productivity, throughputs, and stabilization of the process. An investigation of CMP process variables on AE signals were carried out at the University of California-Berkeley to verify the AE sensitivity to the fundamental CMP parameters. Detailed results were presented to the Material Research Society.[14]

Tests to verify the feasibility of using AE for process stability monitoring were carried out at AMD on a Strasbaugh CMP machine. Figure 3 shows a typical AE rms signal in the CMP process from the AMD tests. By observing the AE rms signals, the CMP process can be classified into three stages: namely (I) loading stage, (II) self-accommodation stage or running-in stage, and (III) equilibrium stage. The analysis of each stage is detailed in below.

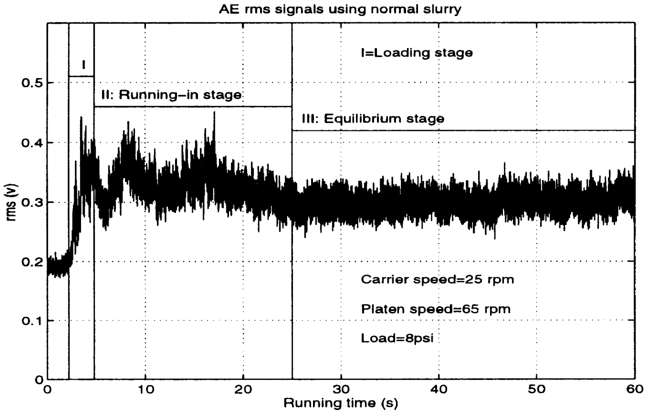


Fig. 3. Typical AE rms signal in conventinal CMP process, Strasbaugh machine.

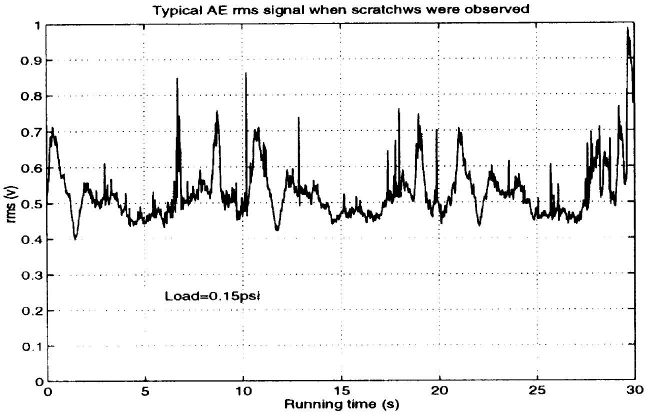


Fig. 4. AE rms signal when a large amount of scratches were observed, LMA machine.

Loading Stage

This stage lasts for about 2–3 s. The AE rms signal rises when the wafer initially contacts the polishing pad and increases with increasing load applied to the backside of the wafer. The AE rms signal reaches its peak value while the load is maximum.

Self-Accommodation Stage

In CMP, this stage is characterized by the unsteady conditions of friction due to the set-down of a wafer on the pad. This stage is also called "running in" mode of operation when the geometry of the contacting surface and the physical-mechanical characteristics of the layers may undergo considerable changes. The above features are represented by the substantial variation in friction and contact states and can be clearly identified from the AE rms signals. The self-accommodation stage can extend from several seconds to several tens of seconds depending on the initial contact impact and on the properties of the pad and the wafer film layers.

Equilibrium Stage

This stage shows the stabilization period in the material removal rate and the establishment of an equilibrium surface roughness generated by the CMP. The stabilization of the AE signal (i.e., constant level

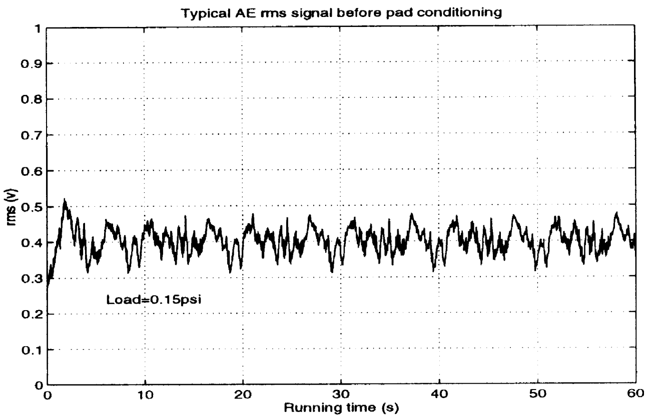


Fig. 5. AE rms signal before pad conditioning, LMA machine.

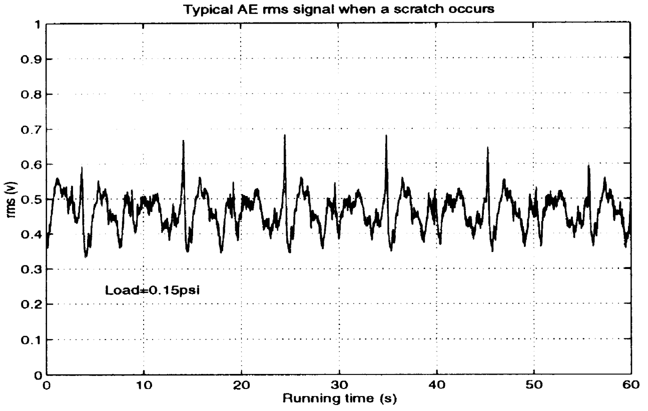


Fig. 6. AE rms signal after pad conditioning with large grit present, LMA machine.

and low variance) coincides with this stabilized CMP process.

The relative length of the first two stages may have important influences on the nonuniform material removal rate during CMP and will be investigated in detail in the future. The experiments at AMD also showed that the AE sensing system developed in LMA could be easily integrated into a commercial CMP machine.

IN-PROCESS PREDICTION AND/OR DETECTION OF MICROSCRATCHES CAUSED BY SLURRY CONTAMINATION OR LARGE PARTICLES FROM THE CONDITIONING WHEEL

Two sets of primary tests were carried out in Berkeley to verify the feasibility of using AE for microscratch detection in a CMP process. In the first set of tests, large diamond grits (here 1 μm) were artificially added to the slurry during CMP and the corresponding AE signals collected. In this case, a large number of mixed microscratches were observed in the polished wafer. Correspondingly, several spikes appeared in the AE rms signals in each wafer carrier rotation period (about 9 s in this test), see Fig. 4, especially as the pad/wafer gap decreased at lower speeds. In another test, we conditioned a pad utilizing a diamond wheel composed of 250 μm grits and compared the AE signals in a CMP process before and after conditioning. The AE rms signal before pad conditioning is shown in Fig. 5. When the large grit was introduced during pad conditioning, a regular spiral shape scratch was observed in the wafer surface after CMP. The corresponding AE rms signals are shown in Fig. 6. The larger spike which appeared in each rotation period of the wafer carrier was believed to be related to the regular spiral shape scratch.

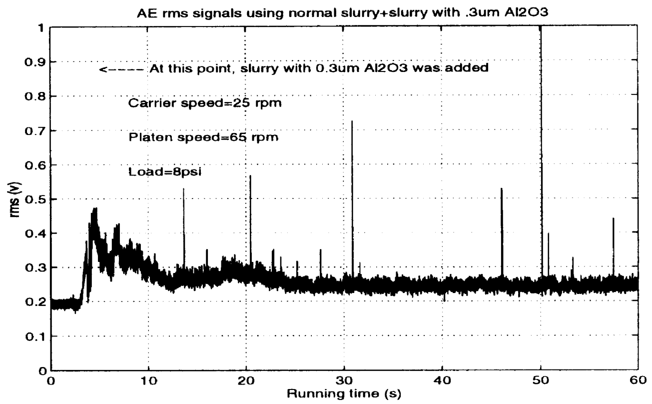


Fig. 7. AE rms signal when using SC112 silica based slurry + slurry with fine Al_2O_3 particles, Strasbaugh machine.

Similar tests at AMD were conducted on a Strasbaugh CMP machine to verify the sensitivity of AE signals to the microscratches caused by slurry contamination. Two slurries were used: (1) SC112 silica based slurry (particle size is about 140 nm); (2) SC112 silica based slurry + slurry with fine Al_2O_3 particles. The corresponding signals are shown in Fig. 3 and Fig. 7, respectively. Similar spikes in Fig. 7 are considered to be related to microscratching occurring in the CMP process.

Since the microscratch generated in the earlier polishing will be removed by the continuing polishing, based on the information of the AE rms and by properly choosing the endpoint of polishing, microscratch could be avoided. For example in the test at AMD, the polishing rate is about 16 nm/s, and the scratch depth is usually in the range of 40–60 nm, therefore in Fig. 7, the scratch generated from 0–55 s will be removed by the polishing from 55–60 s. Only one scratch generated at about 57 s will remain on the wafer surface. If scratch free polishing lasts for a couple more seconds, a scratch free wafer surface could be obtained. Therefore, when considering the CMP endpoint, if the film thickness tolerance allows, a scratch free endpoint could be a better endpoint to stop the polishing.

CONCLUSIONS

The objective of this research was the development and evaluation of a sensing technique for microscratch detection and process characterization during chemical mechanical planarization. The following conclusions can be made:

- Measuring the AE signals from the spindle housing of the commercial CMP machine was found to provide satisfactory sensitivity for the CMP process characterization and microscratch detection. The AE sensing system developed in the LMA could be easily integrated to a commercial CMP machine.

- The CMP process can be classified into three stages by observing the AE rms signals recorded: namely (I) loading stage, (II) self-accommodation stage, and (III) equilibrium stage. A transition from self-accommodation to steady stage in CMP can be clearly identified by observing the AE rms signal, which could be used for controlling CMP process stability.
- The sensitivity of AE signals to the microscratching occurring during CMP was verified. A sharp peak value in AE rms was observed while scratches occurred on the wafer surface. This feature could be used for in-process scratch detection in CMP planarization.
- Based on the position of a spike of the AE rms signal and by properly choosing the endpoint of polishing, microscratches could be avoided.
- Future work will be focused on (a) developing a wave guide which can be installed into a commercial CMP machine to improve the signal transmission efficiency from the source to the sensor so as to improve the sensing sensitivity; and (b) developing a quantitative model for scratch formation in CMP using hardness values of both pad and dielectric materials and particle geometric values.

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