Effects of Slurry Flow Rate and Pad Conditioning Temperature on Dishing, Erosion and Metal Loss During Copper CMP

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Abstract

Chemical-mechanical planarization (CMP) process is capable of achieving a global planarity across the wafer, and hence, is widely applied for fabrication of multi-level metallization structures, which are being adopted to reduce interconnect delay. Though the CMP is highly effective, there are defects that arise during the process and significantly impact the final device yield. Thus, it is very important to investigate the sources of these defects. In the present research, the effects of slurry flow rate and polishing pad temperature on the generation of dishing, erosion and metal loss during copper CMP process have been investigated using a bench-top polisher CP-4. Patterned copper wafer coupons were polished with varying polishing pressure and slurry flow rate using conventional slurry and pads. The post-CMP imaging of the patterned wafer surfaces was carried out to characterize wafer defects, using an AFM integrated into the tester UNMT-1. Also, the erosion and metal loss data at dense features both thin and wide, were measured using a surface profiler. The study ascertains a correlation between process parameters and the extent of planarity defects.

Key words: flow rate, dishing, conditioning, temperature
Introduction

Copper CMP is being widely researched to better understand and improve the damascene process of IC fabrication. Due to the pattern density variations across the wafer, there is a difference in individual removal rates and step height reductions of patterns mainly depending on the density and width of the pattern lines. Due to this inconsistent removal rate, global planarization faces issues like non-uniformity within a single die subsequently leading to defects like dishing and erosion of the interconnect materials. Dishing and erosion account to a major portion of the yield losses during manufacturing. Dishing is the loss of the copper from the copper lines resulting in a deviation from the desired flatness of the metallization layer [1, 2]. Erosion is the loss of dielectric material due to its removal during over polishing step (practiced in order to remove even the final trace of copper between the metal lines). There are many factors that influence the generation of these anomalies on the surface. Some of such factors are width of the lines, pattern density, down force, and physical properties of the polishing pads. Even though models and investigations have been done in the past [3-5] to investigate the effect of down force, slurry chemistry and pattern dependencies, very little effort has been put into studying in depth the sources of generation of dishing and erosion. In the current study, the effects of slurry flow rate, polishing pad temperature at the interface, and pad conditioning on dishing, erosion, and metal loss are being studied. The slurry being delivered at the interface of the pad and wafer contact, takes away major part of the heat from the interface through convective heat transfer [6-9]. The amount of heat dissipated at the interface is crucial in the process of CMP. Heat dissipated is found to impact the removal rate due to the changes it brings in the chemical kinetics and in
physical properties of the polishing pad [7-9]. The polishing pad is shown to soften due to
the temperature increase, and so the area of contact at the interface increases [6, 8]. As per
the previous investigations, down-force and pattern line width have a substantial influence
on dishing depth. This indicates a predominant role of the mechanical aspect of polishing on
the generation of dishing. The slurry film at the interface plays a role in the intensity of
mechanical force being applied during CMP. Thus understanding the effects of slurry flow
rate and pad surface temperature during copper CMP process on the generation of dishing
and erosion is very crucial in order to minimize defects and maximize yield.

Pad conditioning has been proven to have a significant effect on the removal rate during
CMP processes. Under-conditioned pads are prone to glazing effect on their surfaces
resulting in reduction of surface roughness, thus eventually lowering the removal rates.
Slurry acts as a cooling agent as it carries away heat dissipated at the interface through
convection mechanism. Thus, it is hypothesized that slurry flow rate impacts the pad
temperature during polishing. In the present study, the effect of pad temperature on the
dishing and erosion was investigated as an extension to the slurry flow effects. Long pad
conditioning experiments using water at different temperatures were carried out in order to
investigate the changes in the coefficient of friction of the pad with changing conditioning
temperature and its subsequent effects on the copper CMP performance.
Experimental equipment

The polishing experiments were conducted on a bench-top CMP machine model CP-4, manufactured by CETR Inc. (refer Fig. 1). This polisher provides a fully controlled CMP process, which imitates closely any large-wafer fab production processes, with the following five motions:

- active rotation of the lower platen with polishing pad (which facilitates polishing) with a speed range 0.1 - 600 rpm,
- active rotation of the upper wafer (which makes the polish more uniform) with a speed range 0.1 - 600 rpm,
- passive rotation (from the pad) of the upper conditioner (which makes the pad conditioning more uniform),
- active linear reciprocation of both the upper wafer and conditioner (which makes the polish more uniform) with a speed range 5 - 600 mm/min,
- active slurry flow (for polish) and DI-water flow (for conditioning) from pumps with adjustable flow-rates in wide ranges.

The polisher can accommodate 2” to 4” wafers, the platen can hold up to a 9” pad. Both in-situ and ex-situ conditioning are available. During the CMP process, the following seven process parameters are continuously monitored in-situ at a total sampling rate of 20 KHz and recorded:

- down-force on the wafer (which is servo-controlled to maintain constant),
- friction force (torque) and coefficient in the wafer-pad interface, which changes between wafer layers indicate the material removal time and allow for calculation of removal rate [10, 11],
- down-force on the conditioner,
- friction force and coefficient in the conditioner-pad interface, which changes allow for precise detection of the start-point and end-point of conditioning [12],
- pad wear (pad cut rate),
- temperature in the slurry and/or on the pad,
- contact acoustic emission in the wafer-pad interface, which average level allows for evaluation of polishing intensity and peaks allow for detection of wafer scratching and layer delamination processes [10].

The in-situ monitoring of the coefficient of friction between the wafer and the pad helps understand the tribological mechanisms occurring at the interface, and also facilitates precise end point detection of the polishing process. The in-situ monitoring of the coefficient of friction between the conditioner and the pad facilitates precise detection of start and end points of conditioning and allows for optimization of the pad conditioning process.

Polishing tests can be sequentially programmed to carry out cleaning procedures with water through one pump after the polishing process which uses slurry from another pump. Further details and capabilities of the instrument are discussed elsewhere [10,13,14]. Programmable forces, speeds and slurry flow rates allow to closely imitate fab CMP processes on any production polisher and to understand the processes in detail. This bench-top instrument is
highly economical in research and development environment for consumable characterization and process development because of savings on process consumables. In-situ conditioning was done using a soft abrasive conditioner, and ex-situ conditioning was done using a hard diamond conditioner. The pad surface temperatures during polishing were measured using thermocouples placed very close to the trailing edge of wafer carrier.

Post-CMP surface characterization was carried out using both KLA-Tencor surface profiler and Pacific Nanotechnology (PNI) atomic force microscope integrated with the Universal Nano+Micro Tester (UNMT-1), manufactured by CETR Inc. The AFM is capable of performing multiple scans (automated) over the sample surface using a procedure called “move-n-scan”. This procedure allows the instrument to image at several locations on the wafer and save the images simultaneously in a single operation. The UNMT-1 with AFM head is used for large-area automated multi-scanning and facilitates imaging of multiple locations on wafers up to 8” in diameter. Its large sample stage can rotate with a sub-micron angular positioning resolution, while the AFM head on the lateral slider has a long translational motion to provide precision positioning on various wafer radii. The ability to perform multiple images over a wafer makes this instrument an economical alternative to atomic force profilers currently used in the industry.

The co-ordinates of the features on the wafers were pre-determined to be used as inputs to the “move-n-scan” procedure. The AFM was operated in the contact mode imaging, scanning in the direction perpendicular to the direction of cantilever holding the tip. Scan size was set at 80 µm, frequency of the cantilever was set at 1 Hz. The post processing
Nanorule software allows improving the resolution of the image. Once the imaging was done, a line analysis was performed and an average of 10 dishing depth measurements on every image was taken to obtain statistically meaningful data.

The measurements of metal loss and erosion were performed on the KLA-Tencor surface profiler, as imaging of the total pattern width of 1500 µm is not possible on AFM due to scan size limits. Similarly, 10 measurements at each feature were taken on the profiler.

**Experimental Procedures and Samples**

In the present research, the effects of slurry flow rate were studied in the first series of experiments, the effects of pad temperature and conditioning on the generation of wafer defects during polishing were studied in the second series of experiments. The consumables and the polishing parameters employed for the experimentation are presented in Table. 1. The chosen slurry flow rates scale up to the range of 100 ml/min – 375 ml/min on an 8” wafer polishing system. In-situ conditioning at 4 psi during polishing experiments and ex-situ conditioning during pad conditioning experiments were carried out.

The polishing experiments constituted of preliminary tests for removal rate determination and main tests for dishing and erosion characteristics. The preliminary tests for removal rate were conducted with varying slurry flow rate. The end-point of copper planarization was determined from the coefficient of friction changes during polishing, which shows a characteristic transition at the time of copper removal as the underlying barrier layer is
exposed (see Fig. 2). Thus, removal times and removal rates were estimated. The main tests for dishing and erosion characteristics were then carried out at varying slurry flow rate with a 20% over-polish time to fully expose the underlying barrier layer.

The second series of experiments included ex-situ pad conditioning for 10 min at different water temperatures to further investigate the effect of temperature on the conditioning process. Polishing was subsequently conducted to study the effects of changes in conditioning process on CMP performance in regard to dishing and non-uniformity. Pad was maintained at the temperature of water used for conditioning during the short period of time between the conditioning and polishing processes.

Patterned 2” wafers with 10 kÅ electroplated copper layers and an MIT 854 pattern were used for our experiments [15]. The pattern consists of different line widths ranging from 0.18 μm to 100 μm and pattern densities ranging from 1% to 100%. Its layout is presented in Fig. 3. Isolated lines of 50 μm wide at two locations from a single die were chosen for dishing depth measurements. Two wide metal line patterns, 50 μm line width with 98% density and 100 μm line width with 99% density, were chosen from each die for metal loss data. Two thin metal line patterns, 10 μm line with 50% density and 1.5 μm line with 67% density were chosen from each die for erosion data. Thus, 8 locations per wafer were available for dishing, erosion and metal loss measurements.
Results and Discussion

The coefficient of friction between the pad and wafer surface during polishing and removal rate data from the first series of slurry flow rate experiments are presented in Fig. 4. The dishing, metal loss and erosion data, plotted versus slurry flow rate, are presented in Figure 5. Polishing was repeated 4 times at each condition to confirm data reproducibility. The numerical values in Figures 4 and 5 are averages of data collected from four samples polished at each slurry flow rate. Y-axis error bars represent the standard deviation of the data about the average values. Fig. 6 shows AFM images of dishing profiles of 50 µm features at different slurry flow rates.

From the Fig-s 2 and 4 it can be seen that coefficient of friction decreased and removal rate increased with an increase in slurry flow rate. As the higher flow rate decreases the temperature at the interface, the observed decrease in coefficient of friction is in agreement with the results from other investigations [9, 16]. The observed trend of the removal rate can be attributed to the inadequate chemical component during polishing at lower slurry flow rates. During CMP process, slurry should act as both a surface oxidant and dissolver of the fragments of copper detached from the wafer surface. If the amount of slurry available on the pad is not sufficient to carry out these chemical activities, the removal rates decrease.

From Figure 5 it can be seen that all the three levels of dishing, erosion and metal loss decreased with an increase in slurry flow rate. The reason for high dishing, erosion and metal loss at low slurry flow rates may be due to relatively high temperatures at the
interface, causing local softening of the pad. The asperities of a softer pad reach deeper into the trenches compared to the stiffer pads, resulting in increase of dishing, erosion and metal loss. The rise in the pad surface temperature during polishing experiments with different slurry flow rates is shown in Fig. 7, which shows that a rise in pad temperature decreased with increase in slurry flow rate.

To further confirm the effect of pad softening, the second series of experiments with pad conditioning at different temperatures was carried out with subsequent copper polishing. The pad surface temperature transients associated with conditioning experiments are presented in Fig. 8. The mean values of the coefficient of friction along with standard deviation are plotted against the pad conditioning temperature in Fig. 9. It can be seen that friction between the pad and conditioner increased with increase in temperature during conditioning. The pad-conditioner coefficient of friction values during conditioning, plotted versus time are presented in Fig. 10. The coefficient of friction stabilized faster during conditioning at lower temperatures than at higher temperatures. The stabilization of the coefficient of friction is a measure of the end of conditioning process [12]. Thus, longer conditioning was required for full pad conditioning at higher temperatures. Loss of pad material during conditioning directly affects the pad life time. As the pad loss increases, pad life time decreases, and so, pads need to be replaced more often. This increases the cost of consumables and the machine down time, which in turn negatively affects the throughput of CMP process and overall process operational costs. Hence, it is crucial to monitor the pad loss during conditioning process. The real-time change in pad thickness and accordingly the pad cut rate during conditioning at different temperatures are presented in Figures 11 and 12.
The pad loss was high at lowest temperature and decreased thereafter with increase in water temperature. The loss in pad thickness at 38°C was almost negligible compared to pad loss for conditioning process at 10°C. These observations indicate an aggressive conditioning process at lower temperatures, as compared to the elevated temperatures.

To study the effect of the change in pad conditioning, patterned copper samples were subsequently polished. Post CMP samples were accordingly analyzed for their dishing characteristics. The removal rate and coefficient of friction from these tests are plotted versus pad conditioning temperature as shown in Fig. 13. The friction and removal rate values were higher when the pad was conditioned at temperatures below the room temperature. This is attributed to the hardening of polishing pad due to lower temperatures. The removal rate and coefficient of friction values were the lowest at the room temperature and they rose as the temperature was elevated above the ambient temperature. This may be a result of increased chemical action of copper with the slurry in accordance with the arrhenius relation, as well as of increased area of contact due to softening of the pad [7, 8] resulting in increased shear force. The dishing values on these samples were measured and found to be increasing with increase in pad temperature as shown in Fig. 14. It can also be noticed that the deviation from mean value decreased with increase in pad temperature. The standard deviation in Fig. 14 signifies the variation of dishing depths at different locations on the sample. This indicates that the level of non-uniformity in the polishing process decreased considerably for the wafers polished after conditioning the pad at elevated temperatures. The fact that the absolute values of dishing increased with increase in pad
temperature even with improved polishing uniformity, supports the earlier result that greater amount of dishing occurs when the increase in pad temperature is high.

**Conclusions**

1. The effects of slurry flow rate, pad temperature and conditioning temperature on the copper CMP performance have been studied.

2. During copper CMP process, higher slurry flow rates resulted in decreased levels of friction, dishing, erosion and metal loss, while increased copper removal rate.

3. During ex-situ pad conditioning, friction reached steady-state faster at lower temperatures comparing to the elevated temperatures, thus, full-conditioning at higher temperatures was longer.

4. Higher removal rates and coefficient of friction between pad and wafer surface were noted at both very low and very high temperatures of conditioning.

5. Post-CMP dishing increased with increase in the pad temperature.

6. Pad temperatures during both conditioning and polishing play a major role in the generation of wafer defects like dishing and erosion during copper CMP process.
Tables

Table. 1 Consumables and process parameters in polishing experiments

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer coupons 2”</td>
<td>10,000 Å copper over patterned low-K dielectric</td>
</tr>
<tr>
<td>Polishing Pad</td>
<td>IC 1000 perforated/ Suba IV sub pad</td>
</tr>
<tr>
<td>Slurry</td>
<td>I-cue 5001 copper slurry</td>
</tr>
<tr>
<td>Oxidizer</td>
<td>30% hydrogen peroxide</td>
</tr>
<tr>
<td>Slurry Flow rates</td>
<td>20, 30, 45, 55 and 75 ml/min</td>
</tr>
<tr>
<td>Polishing Pressure</td>
<td>4 psi</td>
</tr>
<tr>
<td>Velocity</td>
<td>Wafer carrier – 95 RPM; Polishing pad – 100 RPM</td>
</tr>
<tr>
<td>Slider motion</td>
<td>5 mm offset at a speed of 1 mm/sec</td>
</tr>
<tr>
<td>In-situ conditioning pressure</td>
<td>4 psi</td>
</tr>
<tr>
<td>Ex-situ conditioning pressure and RPM</td>
<td>4 psi and 150 RPM</td>
</tr>
<tr>
<td>Water Flow Rate during conditioning</td>
<td>200 ml/min</td>
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