Feasibility of real-time detection of abnormality in inter layer dielectric slurry during chemical mechanical planarization using frictional analysis

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Abstract

Material removal rate, coefficient of friction, shear force and variance of shear force of pure and contaminated slurries are studied using spectral analysis of the frictional force. Larger abrasive particles are introduced into commercially available inter layer dielectric chemical mechanical planarization slurry to explore this effect. Results show that trace amounts of larger abrasive particles are transported effectively to the pad–wafer region during polishing. With certain type of consumables investigated in this study, results indicate that contaminated slurry does not significantly change removal rate, however it induces significantly higher coefficient of friction, shear force and variance of shear force than pure slurry. Spectral analysis based on the raw shear force data is employed to elucidate the fundamental physical phenomena during inter layer dielectric chemical mechanical planarization. Fast Fourier Transformation is performed to convert the shear force data from time domain to frequency domain. The energy distribution of polishing using pure and contaminated slurry is quantified to elucidate the effect of trace amount of larger particles. This work also underscores the importance of real-time detection on chemical mechanical planarization process to detect slurries abnormality.

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1. Introduction

Chemical mechanical planarization (CMP) of dielectric and metal layers has been proven to be the most effective technique for multilevel planarization of integrated circuit (IC) fabrication in the semiconductor industry. CMP technology enables global and local planarization to meet the increasingly stringent lithographic requirements of device manufacturing. The non-planar dielectric or metal films resulting from thermal growth, chemical vapor deposition or electrodeposition on patterned wafers have to be planarized using CMP before subsequent processing. As IC devices shrink to the nano-scale dimension, micro-scratches become a major defect problem that can lead to severe circuit failure and yield loss.

During CMP, the wafer is pressed down against a rotating polishing pad. Slurry is injected to the polishing pad. The polishing pad asperities and grooves play important roles in holding the slurry. The rotation of the pad and wafer carrier accommodate slurry transportation to the wafer-pad region. It has been investigated that abrasive particles agglomeration, large abrasive particles as well as the solidified particles generated along the slurry supply system are the main causes of the defect formation during polishing[1,2]. Mechanical abrasion by the larger abrasives particles is the major mechanism creating micro-scratches [3]. Basim et al. showed that more micro-scratches are produced during interlayer dielectric (ILD) CMP as the size and the number of large particle are increased [4]. If critical defects are formed in the wafer surface, the wafer may be totally discarded. Otherwise, it requires further re-processing which decreases overall throughput. Hence, it is of a great interest to develop a method to detect such abnormalities in real-time during polishing.
Filtration along the slurry supply system has been the preferred technique to prevent defect causing particle to enter the polishing system. Seo et al. [1,2] reported that the filtration technique effectively reduced defect density after the ILD CMP process. However, the effectiveness of filtration depends on the filter lifetime and its reliability. The defect formation becomes significant when the filter fails or reaches end of life. Hence, a real-time detection along the slurry system is required.

Numerous studies have focused on detecting changes in the large particle tail of the slurry particle size distribution (PSD) when the slurry is subjected to handling conditions in the supply system. Previous studies indicated that single particle optical techniques are the most sensitive of several techniques tested for measuring changes in the large particle tail of slurry PSD [5]. The rate of formation of particle agglomerations from small particles is measured in-situ along the slurry supply system [5]. However, Basim et al. [6] indicated that abrasive particles in injected slurry tend to agglomerate during polishing process due to fluctuations in local particles or salt concentration under dynamic processing conditions. Hence, real-time methodologies are needed to give an advance warning as to detecting the presence of defect causing particles involved during polishing process.

This study explores the detection of large particles using shear force measurement during ILD CMP. Removal rate is also measured to identify the effect of abrasive particles on material removal mechanism. Additionally, spectral analysis based on the raw shear force data is investigated to elucidate the fundamental physical phenomena on the effect of abrasive particle size in CMP process. Fast Fourier Transformation (FFT) is performed to convert the shear force data from time domain to frequency domain. The normalized versions of the frequency domain are shown to indicate the energy distribution of stick-slip phenomena associated with each polishing condition. Lastly, the feasibility of this method to detect abnormalities in the slurry in real-time during CMP process is explored.

2. Experimental apparatus and procedure

A scaled version of a Speedfam-IPEC 472 polisher was constructed for this study. The main body consisted of Struers Rotopol-35 polisher. A drill press was modified to include a direct current motor which provided rotation and down force to the wafer during polishing. To apply a given load to the wafer, a traverse with a weighted carriage, was mounted atop the drill press. The slurry injector position was fixed on the pad center. The conditioner was mounted on the polisher. During polishing, both the pad and the wafer carrier rotated in a counterclockwise fashion. All polishing parameters were computer controlled and monitored. The computer synchronized the friction table to the polishing process so that real-time friction data could be obtained during polishing [7,8].

To measure the shear force between the pad and the wafer during polish, a sliding table was placed beneath the polisher as shown in Fig. 1. The sliding table consisted of a bottom and a top plate upon which the polisher was set. As the wafer and pad were engaged, the top plate slide with respect to the bottom plate only in one direction due to friction between pad and wafer. The degree of sliding was quantified by coupling the two plates to a load cell. The load cell was attached to a strain gauge amplifier that sent a voltage signal to a data acquisition board. The apparatus was calibrated to report the force associated with a particular voltage reading. In this study, the shear force data was taken with frequency of 1000 Hz.

Prior to data acquisition, the pad was conditioned with a 100-grit diamond disc rotating at 30 rpm and oscillating at 0.33 Hz. The load applied to the diamond disc was 3.45 kPa. The above conditions were also used for the in-situ conditioning during polishing to ensure the regeneration of pad asperities. Ali and Roy [9] postulated that the degradation in the removal rate of pad without conditioning is due to the decrease in the slurry holding capacity of the pad since the pad asperities play critical role on transporting the slurry as well as its abrasive particles. Pad conditioning was done for 30 min with ultra-pure water. Pad conditioning was followed by a 5-minute pad break-in using the slurry. The slurry flow rate was kept constant at $1.33 \times 10^{-3}$ L/s. Following the pad break-in, five monitor wafers were polished to confirm the consistency of coefficient of friction measurements.

Polishing was performed for 75 s on 0.1 m silicon wafers with $6 \times 10^{-7}$ m blanket thermal oxide. Polishing was done on Rohm and Haas IC1020 M-Groove pad. The polishing pressure was 28 kPa and the pad–wafer sliding velocity was 1.12 m/s. The slurries were Fujiimi PL-4217 12.5% w/w of $1 \times 10^{-7}$ m abrasive silica and Fujiimi PL-4217 12.5% w/w of $1 \times 10^{-7}$ m abrasive silica contaminated with 0.5% w/w of $9 \times 10^{-7}$ m abrasive silica.
alumina. In this paper, when discussing slurry types, it is preferred to use shorter names: pure and contaminated slurry. The slurry kinematic viscosity is about $2 \times 10^{-6}$ m$^2$/s.

Several research groups have recently shown that the particles of about $1 \times 10^{-6}$ m or larger in diameter cause wafer defects in CMP [2,5,10]. Therefore, the addition of $9 \times 10^{-7}$ m large particles in the pure slurry in this study is well-representative of contamination in slurry simulating defect causing particles. In a separate study, Basim et al. [4] demonstrated that the contamination of commercial slurry with 1% w/w larger abrasive particle size resulted in an increase of surface roughness and a higher number of surface defects. Hence, the addition of 0.5% w/w of larger particle in this study is acceptable for studying the feasibility of real-time detection of slurry abnormality.

After polishing, oxide wafers were rinsed and dried. The removal rate was calculated based on the difference of mean oxide thickness between pre- and post-polishing acquired by a reflectometer from SENTECH Instruments GmbH.

3. Theoretical approach

Coefficient of Friction (COF) and Spectral Analysis. — In CMP, COF is defined as the ratio of mean shear force during polishing to the applied wafer down force to the polishing pad. In this study, shear force is collected at a sampling frequency of 1000 Hz throughout polishing process. Fig. 2 shows the raw shear force measurement during CMP. The mean force, $F$, which represents the average of all data points, is used in calculating COF as defined above.

The measured total unidirectional shear force as a function of time, $F(t)$ shown in Fig. 3(a) can be broken into two components: the mean shear force of the system, $F_s$, and the fluctuating shear force component, $f(t)$. For spectral analysis, the mean shear force, $F$, can be subtracted from shear force, $F(t)$, to extract the fluctuating component, $f(t)$. Fig. 3(b) shows the fluctuating component of shear force data in time domain. The fluctuating component corresponds to the intrinsic vibration of the polisher as well as stick-slip phenomena of the system. Stick-slip phenomena are defined as the sticking and slipping of two solid bodies among pad, wafer and abrasive particles during CMP. Generally speaking, the stick-slip phenomena closely relates to the material removal rate mechanism. Sticking happens when the abrasive particle embedded to the soft layer in the
polished substrate surface and the subsequent slipping occurs to remove the layer. Therefore, there are certain frequencies related to the stick-slip phenomena during CMP which can be identified using FFT by converting the time domain of the fluctuating component of shear force into frequency domain as shown in Fig. 3(c). The y-axis shows the magnitude of the spectral amplitude in logarithmic scale in order to show wider range. The x-axis represents the frequency associated with the fluctuating component of the shear force. The maximum frequency reported in this study is 500 Hz which is the Nyquist frequency of sampling rate at 1000 Hz. The Nyquist frequency is the maximum frequency that can be computed at a given sampling rate in order to be able to fully process the shear force signal without aliasing problem [11,12]. In order to show more clearly the energy distribution, the amplitude is normalized as shown in Fig. 3(d). The cumulative value of the normalized amplitude up to 500 Hz is equal to one.

Fig. 4 shows the spectral analysis as well as the normalized version of three different runs using the same polishing condition and consumables. It can be observed that the results are consistent on both magnitude and distribution. This is the key of studying the stick-slip phenomena without having to worry about inconsistency.

4. Results and discussion

In most industrial applications, the content of abrasive particles in the slurry is generally represented by a weight percentage (i.e. total weight of abrasive particles to that of the slurry). However, for slurries that contain two or more types of abrasive particles with different properties (such as size and density), weight percentage is not the best representation for describing the entities. In such cases, it is better to calculate and report the concentration of abrasive particles (i.e. number of abrasive particles per unit volume), hence the number ratio of different abrasive particles in slurry can be quantified.

In this study, 12.5% w/w of fumed silica is mixed with 0.5% w/w of alumina to simulate the contaminated slurry. Using the equation given in the Appendix, it can be calculated that there is about 1 alumina particle in 20,000 silica particles. Table 1 shows that removal rate is not affected by the presence of alumina particles and dominated by fumed silica particles which account for the majority of the abrasive particles in the slurry. On the other hand, coefficient of friction and shear force variance are significantly affected by the presence of infinitesimal amount of alumina particles in the slurry, thereby suggesting that these larger particles actually do actively...
participate in polishing by altering the frictional forces attributes of the process.

Fig. 5 shows the comparison of the raw shear force data using pure and contaminated slurry. The fact that higher shear force is observed in contaminated slurry confirms that the alumina particles are transported effectively to the pad–wafer region. More importantly, it demonstrates that the alumina particles are in intimate contact with the wafer surface within the pad–wafer region. Larger alumina particles plough more severely the silicon oxide surface than silica particles, hence higher shear force.

As shown in Fig. 5, the magnitude of fluctuation of shear force is higher with contaminated slurry than pure one. It is defined that the fluctuating component of shear force corresponds to the deviation from the mean shear force. Further observation on the polishing process shows that the magnitude of such fluctuation correlates to the extent of vibration during CMP process. The magnitude of fluctuation is well represented numerically by calculating the variance of shear force. Generally speaking, higher variance corresponds to a more severe polishing vibration (i.e. less stable polishing process). As summarized in Table 1, contaminated slurry consistently exhibits higher force variance by factor of 3. The presence of larger abrasive particles during CMP process leads to an unequal distribution of applied load on the wafer surface. Later, it can be understood that such un-equal load distribution contributes to the less stable polishing process. Hence, the addition of trace amounts of alumina particles using the type, size and concentration investigated in this study is significant enough to cause a less stable polishing process. Such significant increase in force variance as well as COF associated with the contaminated slurry shows a feasibility to implement frictional measurement technique to detect abnormality in real-time during CMP process.

Table 1
Summary of removal rate, COF and variance of shear force associated with polishing using pure and contaminated slurry

<table>
<thead>
<tr>
<th>Slurry</th>
<th>Removal rate (m/s)</th>
<th>COF</th>
<th>Variance of shear force (N²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure PL-4217</td>
<td>$2.73 \times 10^{-9}$ (9.00 $\times 10^{-11}$)</td>
<td>0.27 (0.01)</td>
<td>26.71 (7.91)</td>
</tr>
<tr>
<td>Contaminated PL-4217</td>
<td>$2.72 \times 10^{-9}$ (2.22 $\times 10^{-10}$)</td>
<td>0.46 (0.01)</td>
<td>84.88 (10.68)</td>
</tr>
</tbody>
</table>

Values in parentheses are standard deviations.

In this study, the magnitude of spectral amplitude between 150 and 500 Hz is low enough to be considered as noise and not giving any important physical and chemical meanings of the CMP process. Hence, it is of great interest to focus only on the first 150 Hz for all of the spectral analysis where the spectral amplitude is pronounced.

In frequency domain as shown in Fig. 4, it is important to understand the presence of particular peaks at particular frequencies. Fig. 4 shows the presence of several peaks ranging in frequencies from 1 to 140 Hz. To determine whether the frequencies at which the peaks were observed were the results of vibrations which were specific to the polisher or the result of wafer–slurry–pad interaction, a simple experiment was performed. The polisher was run with the wafer completely disengaged from the pad as the baseline process. By recording...
the total unidirectional force, and followed by transforming it into frequency domain, the intrinsic vibration of the tool, as shown in Fig. 6, can be compared to the wafer polishing shown in Fig. 4. The spectrum in Fig. 6 clearly indicates that, in the absence of any pad–wafer interaction, the tool vibrates at a dominant frequency of around 10–11 Hz, with harmonic peaks occurring at frequency range of 20–22 Hz. Considerable spectral amplitude in frequencies of 120 and 129 Hz is observed, indicating the tool’s contribution on these particular frequency ranges. It must be noted that 60 Hz shown in the spectral analysis is the frequency of the electrical utility in the laboratory. This particular frequency is also captured well on all of the spectral analysis in a consistent amplitude, as shown in Fig. 4. Therefore, the 60 Hz spectral must be excluded when discussing the spectral analysis of the polishing.

By comparing the spectrum in Fig. 6 to the one shown in Fig. 4, it becomes clear that the fundamental peak at 120–129 Hz and 10–11 Hz with harmonic peaks at 20–22 Hz are direct results of the intrinsic vibration of the tool. On the other hand, peaks occurring at 2, 5, 7, 9, 35, 40 and 42 Hz originated from interactions among pad, wafer and abrasive particles. The lower frequency peak is the result of the kinematics of the process including the rotational velocities of the platen, wafer, and the diamond conditioner. The observed higher frequency peaks are believed to stem from stick-slip phenomena unique to the CMP process.

It can be observed that pure and contaminated slurry induces similar stick-slip signature (Fig. 7). The considerable spectra are similarly distributed on certain stick-slip frequency ranges. However, polishing using contaminated slurry results in higher spectral amplitude than pure slurry. In order to emphasize the differences, the cumulative spectral amplitude is given in Fig. 8. By definition, the cumulative spectral amplitude to Nyquist frequency (i.e. 500 Hz) is proportional to the variance of shear force of a particular polishing. The cumulative spectral amplitude on frequency of about 150 Hz has already approached a steady value, confirming that the spectral in frequency beyond 150 Hz is less important for fundamental physical and chemical analysis.

The interaction between large and small abrasive particles and wafer affects the spectral analysis of the shear force. The large and small particles roll at the same linear velocity since

<table>
<thead>
<tr>
<th>Slurry</th>
<th>0–15 Hz</th>
<th>30–50 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure PL-4217</td>
<td>0.89 (0.22)</td>
<td>0.15 (0.01)</td>
</tr>
<tr>
<td>Contaminated PL-4217</td>
<td>3.54 (0.48)</td>
<td>0.24 (0.01)</td>
</tr>
</tbody>
</table>

Values in parentheses are standard deviations.
the wafer surface drags the particles at equal sliding velocity. Hence, it can be understood that the interaction of the wafer with large particles induces lower rolling frequency compared to small particles in order to achieve the same linear velocity. Such interaction using contaminated slurry is reflected well in the spectral analysis. The majority of the amplitude is dominated by low frequency range of 0–15 Hz, as shown in Fig. 8. Polishing using contaminated slurry shows a tremendous increase in the spectral amplitude compared to pure slurry by factor of 4. The average of cumulative spectral amplitude in frequency range where the peaks are dominant is summarized in Table 2. The average value shows clearly that all polishes using contaminated slurry significantly increase the spectral amplitude of low frequency.

Part of the spectral analysis is the normalized spectral amplitude, as shown in Fig. 9. For each polishing result, spectral amplitude of each frequency is divided by the integral area of the spectral amplitude up to 500 Hz. The cumulative normalized spectral amplitude is to show the energy distribution during polishing as shown in Fig. 10. The average of cumulative normalized spectral amplitude for all polishes is summarized in Table 3. Again, the results consistently show that polishing using contaminated slurry increases significantly the energy distribution of low frequency range from 78% up to 90%. Meanwhile, the energy distribution on higher frequency ranges decreases significantly. These results indicate that the presence of larger particle is not only increasing the absolute spectral amplitude in low frequency range, as shown in Table 2, but also confirming that such increase in low frequency range dominates the energy distribution, as summarized in Table 3.

5. Conclusion

In this study, the effects of trace amounts of larger particles (i.e. alumina) in a commercially available silica based ILD CMP slurry are explored. With the certain types of consumables used in this study, this work showed that larger particles are effectively transported in the pad–wafer region and are in intimate contact with the polished wafer. The presence of infinitesimal concentration ratio of alumina to silica particles does not affect the ILD removal rate. However, contaminated slurries induce significantly higher value of coefficient of friction and shear force variance than the pure slurry. Fast Fourier Transformation is used to change the shear force data from time to frequency domain and to elucidate the stick-slip phenomena of ILD CMP. It is proposed that larger particles induce significantly slower rolling frequencies than smaller particles, hence the presence of larger particle enhances the energy distribution in the low frequency range (i.e. 0–15 Hz) which may be responsible for creating micro-scratches.

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Appendix

The slurry particle concentration is related to the weight percentage of abrasives in the slurry mixture by the equation, derived below,

$$ A_c = \frac{6}{\pi \cdot d_A^3} \left[ \frac{A_p}{\left(1 - \frac{\rho_A}{\rho_f}\right) \times A_p + 100\frac{\rho_A}{\rho_f}} \right] $$

where,

- $A_c$ is concentration of abrasive particles, $\frac{\text{Number of particles}}{\text{m}^3}$
- $A_p$ is the weight percentage of abrasive particles, %
- $d_A$ is the diameter of the abrasive particles, m
- $\rho_A$ is the density of the abrasive particle, $\frac{\text{kg}}{\text{m}^3}$
- $\rho_f$ is the density of the slurry fluid, $\frac{\text{kg}}{\text{m}^3}$

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Density of silica and alumina are 2200 and 3970 \( \text{kg m}^{-3} \). Slurry fluid is dominated by water, hence the density of slurry fluid is assumed to be 1000 \( \text{kg m}^{-3} \).

References