Effects of kinematic variables on nonuniformity in chemical mechanical planarization

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Received 18 November 1999; accepted 16 February 2000

Abstract

The effects of kinematic variables on the nonuniformity of the wafer in chemical mechanical planarization (CMP) are investigated. The nonuniform amount of material removal is calculated by the velocity integral and the experimental nonuniformity is measured. This analysis becomes more important as the wafer size increases and the requirement for within-wafer nonuniformity is more rigorous. The effects of the rotational and translational speeds and carrier eccentricity are discussed. The significance of velocity uniformity is proved based on the analysis and experiment. The wafer size possesses great importance in the nonuniformity. Large eccentricity is useful, while the translation speed of the carrier plays a minor role in view of kinematics. The analysis provides a guide to the design of a process window in CMP. The experimental results support the analytical approach. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Chemical mechanical polishing/planarization (CMP) has emerged recently as a vital processing technique for a higher degree of planarization in submicron VLSI beyond the resolution of 0.35 μm, and is widely accepted for planarizing interlevel dielectrics and the selective removal of aluminum, tungsten, copper and titanium overburden following metal filling of studs and interconnects. As the wiring density in VLSI chips increases and the device size scales down, CMP becomes indispensable during both device fabrication and formation of multilevel interconnects.

CMP involves close encounter between the wafer and pad charged with colloidal slurry. The chemical reaction in CMP softens or hardens the surface material of the wafer. The treated material is then removed by abrasives of dozens of nanometers in diameter, such as silica or
alumina, at the rate of nanometers per second in thickness. Balanced between the chemical and mechanical effects, the process removes material continuously.

Although CMP has been widely used for a few years, the mechanism of the material removal is yet to be explored. The Preston equation [1], empirically found from the experiment of the glass polishing in 1927, has been proposed to predict the material removal rate of CMP. The Preston equation predicts that the material removal rate is proportional to the polishing velocity and the applied pressure. However, the Preston equation lacks an analytical understanding of the kinematic and abrasive cutting aspects. A model of material removal by abrasive cutting was proposed. It provides a part of the analytical ground for the empirical Preston equation [2].

The role of the uniform polishing velocity in the planarization was highlighted [3,4]. Though it is of great importance in the process recipe in CMP practice, the mechanism of influence of the polishing velocity on nonuniformity and the analytic correlation between them remain unexplored. Recently, the relative velocity field between wafer and pad has been constructed, and the optimal selection of the speed of platen and carrier for CMP has been analytically derived [5]. Based on this study, in the present paper, the kinematic analysis is used to predict the nonuniformity in CMP affected by various kinematic variables. Experimental results are obtained and discussed.

2. Kinematic analysis

2.1. Polishing speed and nonuniformity

Fig. 1 illustrates the kinematic parameters of CMP. The relative velocity of any point A on the wafer with respect to the pad ($\vec{V}$) is shown as
\[ \overrightarrow{V} = \overrightarrow{V_c} + \overrightarrow{u} - \overrightarrow{V_p} = \overrightarrow{r_w} \times \omega_c + \overrightarrow{u} - \overrightarrow{r_p} \times \omega_p \]  

(1)

where \( \overrightarrow{V_c} \) is the carrier velocity, \( \overrightarrow{V_p} \) is the pad velocity at that point and \( \overrightarrow{u} \) is the carrier translation speed. The magnitude of the velocity is

\[ V = |\overrightarrow{V}| = |\overrightarrow{r_w} \times \omega_c - \overrightarrow{r_p} \times \omega_p + \overrightarrow{u}| \]  

(2)

The nonuniform polishing velocity between the wafer and the pad at any point is thus determined by kinematic analysis. The maximum variation of the polishing speed is

\[ |V_{max} - V_{min}| = |(R \times \omega_c + (e - R) \times \omega_p) - [(e + R) \times \omega_p - R \times \omega_c]| \]  

\[ = 2R \times |(\omega_p - \omega_c)| \]  

(3)

The magnitude of relative speed affects the material removal rate, while its direction does not. From the existing proposed material removal rate models, one recognizes that the material removal rate is proportional to the relative velocity between the pad and the wafer surface by the power of 1 or 0.5 [1,2,6,7]. Whatever the power of the relative velocity can be, the amount of material being polished is proportional to the integral of the relative velocity. Based on the Preston equation, the integral of the velocity along a period of time \( T \) indicates the amount of material being polished \( M \).

\[ M = \int_{0}^{T} M \, dt = K \cdot P \int_{0}^{T} V \, dt = K \cdot P \cdot \bar{V} \]  

(4)

where \( K \) is the proportionality constant, \( P \) is the applied pressure and \( \bar{V} \) is the integral of velocity \( V \). Eq. (4) can derive the nonuniform material removal resulting from the nonuniform velocity. For this purpose, the nonuniformity in material removal across the wafer can be predicted by

\[ \text{Nonuniformity (\%) = } \frac{\bar{V}_{\text{std}}}{\bar{V}_{\text{avg}}} \times 100\% \]  

(5)

where \( \bar{V}_{\text{std}} \) is the standard deviation of the velocity integral on the wafer, and \( \bar{V}_{\text{avg}} \) is the average velocity integral.

Examples of the calculated polishing speed from Eq. (2) are shown in Fig. 2, where the diameter of the wafer \( D \) is 150 mm; \( e \), the distance between the centers of the pad and wafer, is 160 mm, and \( u \) is zero. Fig. 2 shows that the platen speed majorly determines the level of the polishing speed, while the carrier speed controls the cycle period. The amplitude of the variation of polishing speed is dependent on the difference of the rotational speed between the platen and the carrier.
Fig. 2. Polishing speed and calculated nonuniformity ($D=150$ mm, $u=0$, $e=0.16$ mm): (a) $\omega_p=30$ rpm, $\omega_c=10$ rpm; (b) $\omega_p=50$ rpm, $\omega_c=10$ rpm; (c) $\omega_p=30$ rpm, $\omega_c=70$ rpm; (d) $\omega_p=50$ rpm, $\omega_c=70$ rpm; (e) $\omega_p=30$ rpm, $\omega_c=-10$ rpm.
Fig. 2. (continued)
2.2. Effects of kinematic variables

2.2.1. Platen speed $\omega_p$
Since $r_p$ is much larger than $r_w$, and $u$ is quite small compared with $V_c$ and $V_p$, $\omega_p$ is the dominant polishing speed ($V$). In fact, the orientation of $\omega_p$ and $\omega_c$ is set to be identical, otherwise the variation in the relative speed at a given point will be too large for practice. One notices from Fig. 2 that the polishing speed increases with $\omega_p$. Fig. 3 summarizes 16 kinematic conditions during CMP. It shows that the nonuniformity increases with $\omega_p$ when $\omega_p > \omega_c$, decreases with $\omega_p$ when $\omega_p < \omega_c$, and the sensitivity of variation increases with $\omega_c$.

2.2.2. Carrier speed $\omega_c$
$\omega_c$ mainly affects the resulting cycle frequency of the polishing speed; the frequency increases with increasing $\omega_c$. Its effects on the nonuniformity are revealed in Section 2.2.1. $\omega_c$ should have an appropriate value adapted to $\omega_p$, which is usually obtained from the processing experience.

Fig. 3 predicts that the lowest nonuniformity is zero when $\bar{\omega}_p$ and $\bar{\omega}_c$ are equal. Though this single result is acknowledged by both the shop floor and researchers, a complete kinematic map is established in the present work. The ratio of $\omega_c$ to $\omega_p$ can be used to describe the relationship between the rotational speeds and the nonuniformity. Several representative cases are shown in Fig. 3 and Table 1. In the case of $-1 \leq (\omega_c - \omega_p)/\omega_p \leq 1$, nonuniformity remains less than 1%, and
The results suggest a process window for a uniform CMP, in consideration of the kinematic uniformity, as follows:

$$h_5 | w_c - w_p | \leq 1 \quad (6)$$

where $h$ is called the index of speed window.

This proposed rule implies the rotational speeds of carrier and platen should be close to each other, and the high platen speed is advantageous kinematically. The former is more feasible and will be examined experimentally in the following section. The latter, however, is limited by the healthy slurry distribution and the chemical interaction between particles and wafer. If the rotational speed of the platen is too large, sufficient time is not provided for both conditions vital for successful planarization. Fig. 4 shows the relationship between the nonuniformity and the speed window index $\eta$ for a carrier eccentricity of 160 mm. It shows that the nonuniformity increases with increasing deviation between carrier speed and platen speed. However, the effects are milder at the range shown by Eq. (6), and the nonuniformity becomes absolutely unacceptable when $\eta$ goes beyond 2.

2.2.3. Carrier eccentricity $e$

Fig. 5 and Table 1 show that the nonuniformity is slightly improved when the carrier translates at large eccentricity relative to the pad center, and worsened at small eccentricity. The polishing
Table 1
Calculated nonuniformity

<table>
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<th>$\omega_p$ (rpm)</th>
<th>$\omega_c$ (rpm)</th>
<th>$\eta$</th>
<th>Nonuniformity (%)</th>
<th>$u=0$, $e=160$ mm</th>
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<th>$u=1$ mm/s, $e=230–290$ mm</th>
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speed increases gradually as the carrier translates outwards on the pad, where the pad velocity increases. The influence is similar to that discussed in Section 2.2.1. The relationship between the nonuniformity and the eccentricity $e$ at varying speed window index ($\eta$) is shown in Fig. 6; the nonuniformity increases with increasing eccentricity. The far rim of the pad provides a large polishing speed relative to carrier speed, which is advantageous for the kinematic uniformity, as discussed in Sections 2.2.1 and 2.2.2.

2.2.4. Carrier translation speed $u$

The effect of carrier translation on the nonuniformity is not significant, as shown in Table 1 and Fig. 7. The results of $u=0$ occur at $e=160$ mm. The translation speed plays no major role in planarization from the kinematic point of view. The current application of carrier translation in CMP, however, is primarily attributed to the maximum utilization of the pad area.

2.2.5. Wafer size $D$

Table 1 and Fig. 8 show that the nonuniformity drastically increases with the wafer size ($D$). The currently discussed kinematic effects possess increasing significance as the challenge of larger wafer size and lower non-uniformity becomes more rigorous. The process window of the kinematic conditions will be significantly narrowed when a large wafer is planarized.
2.3. Absolute uniformity of velocity

When $\omega_p$ equals $\omega_c$, Eq. (2) becomes

$$V = |(r_w - r_p) \times \omega_c + \dot{u}| = |\dot{u} - e \times \omega_c|$$

Since the values of $e$, $\omega_c$ and $u$ are pre-selected, the polishing velocity will be kept constant, i.e. it will not vary with the rotation of both platen and wafer. While such an observation has been reported [3,4], the significance of the derived results has not been fully explored. In this case, the relative velocity is constant at any point across the wafer surface and is called the absolute velocity uniformity. The platen and carrier rotate so that any point on the wafer surface can be polished uniformly, i.e. the amount of material removal remains constant based on the Preston equation. In this case, the nonuniformity is kinematically zero due to the constant velocity at any point on the wafer surface. In a complete rotational period of the wafer, the polishing direction finishes a cycle of 360°, as shown in Fig. 8(a).

When the eccentricity becomes zero, the relative speed is linearly proportional to $r_w$ as shown...
Fig. 5. (continued)
Fig. 5. (continued)

Fig. 6. Relationship between nonuniformity and eccentricity ($D=200$ mm, $u=0$).

- $e=230$–$290$ mm
  - Nonuniformity $=0.18\%$

- $e=160$–$220$ mm
  - Nonuniformity $=0.34\%$
in Fig. 8(b). The velocity field on the wafer is called concentric velocity uniformity. When the eccentricity is infinite, the polishing speed approaches \( r_p \times \omega_p \), which is the case of a linear abrasive-belt polishing in one direction, as shown in Fig. 8(c). The velocity pattern is called linear velocity uniformity. The case of absolute velocity uniformity is experimentally investigated in the following.
3. Experiment

3.1. Experimental method

All the test samples in the present study were grown on P-type (100) 150 mm silicon wafers. The films of silicon dioxide were produced by wet oxidation, in which the silicon was exposed to the oxidizing ambient H₂, O₂ at 980°C. The experiments were carried out on a Westech 372 M polisher using IC 1400 pad and CABOT SS25 slurry. The slurry consists of fumed silica particles suspended in alkali solution. After each polishing, the pad was conditioned. The thickness
of the dielectric films was measured by Nanometrics 2100XP at nine different spots across the wafer, as shown in Fig. 9. Table 2 shows the experimental parameters. The polish rate is defined as the removal rate averaged over the nine locations.

### 3.2. Experimental results

Fig. 3 shows that zero nonuniformity occurs when the platen speed equals the carrier speed, in consideration of the kinematic uniformity. As discussed in Section 2.2.2, good nonuniformity is expected when $\omega_c$ and $\omega_p$ are close to each other. Fig. 10 shows the experimental relationship between the rotational speeds and the nonuniformity at different down pressures. One identifies that low nonuniformity occurs along the diagonal of $\omega_p = \omega_c$ in most cases. High values of nonuniformity are located at large $\omega_c$ and low $\omega_p$, as predicted in Fig. 3. The experimental kinematic conditions for low nonuniformity at various down pressures are summarized in Fig. 11. One notices that whatever the down pressure is, low nonuniformity occurs when the carrier speed is close to the platen speed. For example, the lowest nonuniformity at platen speed 50 rpm lies at the carrier speed of 50 rpm. This result agrees with the kinematic analysis in Section 2 (Fig. 12).

### 4. Conclusions

A kinematic analysis for nonuniformity in CMP is presented and the effects of the kinematic variables are discussed. The results suggest that the nonuniformity is majorly determined by the
Fig. 11. The experimental relationship between the rotational speeds and nonuniformity at down pressures of (a) 10 psi, (b) 8 psi, (c) 5 psi.
ratio between carrier speed and platen speed and the wafer size. The speeds should be kept as close to each other as possible for good uniformity in wafer planarization. The speed window index $\eta$ can describe the kinematic effect in nonuniformity. Carrier translation has a limited effect, and the carrier eccentricity contributes to reduce the nonuniformity. While other non-kinematic concerns, such as the selection of consumables, remain in the current planarization process, the proposed model contributes to the recipe design in practice and possesses increasing significance.
Fig. 12. (continued)
as the challenge of larger wafer size and lower nonuniformity becomes more rigorous. The experimental results agree with the analysis.

References