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Evaluation of advanced chemical mechanical planarization techniques for copper damascene interconnect

K.W. Chen[a], Y.L. Wang[b,d,*], C.P. Liu[e], Kevin Yang[c], L. Chang[a], K.Y. Lo[d], C.W. Liu[b]

[a]*Department of Material Science and Engineering, National Chiao-Tung University, Hsin-Chu, Taiwan, ROC*
[b]*FAB-6 TFE, Taiwan Semiconductor Manufacturing Company, No. 1, Nan-Ke N. Rd., Science-Based Industrial Park Tainan, Hsin-Chu 741-44, Taiwan, ROC*
[c]*Asia IC Mic-Process Inc., Hsin-Chu, Taiwan, ROC*
[d]*Department of Applied Physics, National Chiayi University, Hsin-Chu, Taiwan, ROC*
[e]*Department of Material Science and Engineering, National Cheng Kung University, Tainan, Taiwan, ROC*

Abstract

According to rapid development of CMP technology, the difference of polishing methods would be applied for copper damascene interconnect. These methods include conventional rotary, linear, oscillation platform. The advantages of these platform would highlighted in uniformity control, stability of removal rate, planarization efficiency, throughput promotion, lower cost of ownership, even dishing and erosion effect integrated with slurry. This paper presented our experience to compare the uniformity, removal rate and planarization efficiency of Cu-CMP between various polishing platforms. In convection, the rotary or oscillation platform would be usually applied in oxide and tungsten CMP, due to the robust air-back carrier and rigid platen to polish the wafer, which performs the good reliability on wafer-to-wafer thickness and endpoint detection. However, the linear polisher is made of the air-bearing moving belt and self-rotated carrier and would provide the wider uniformity and planarization control window than others. In addition, the simulation model would explain the difference from mechanic design and wafer moving paths between various polishing techniques. Hence, the trade-off advantage and application between various platforms would be compensated and integrated with slurry, conditioners and coming thickness profile from copper plating. It can achieve the optimization of Cu-CMP process.

Keywords: Copper; Chemical mechanical planarization (CMP); Computer simulation

1. Introduction

Copper chemical mechanical polishing (Cu-CMP) has been an important process in copper interconnect technology. A considerable amount of work has been done in achieving the best planarization, dishing and erosion minimization and polishing control in CMP. There studies mostly addressed on slurry chemical effects [1], pad deformation [2] and the optimization between pattern density and overpolish on copper CMP planarization [3,4]. Although these approaches tended to increase the polishing window, there is still a hampered work and discussion to integrate the various CMP process methods under different electroplating conditions and control the consistent process way in the uniformity and removal rate. For example, in convectional copper electroplating process, there is a phenomenon of faster copper deposition rate on the edge of wafer. It is caused from the non-uniformity of the electric field distribution between multiple electrodes cycled and contacted around wafer edge. The copper plating thickness profile is shown on Fig. 1. Based on the plating result, the CMP process is always requested to increase the edge-polishing rate. However, the requirement with the faster edge-polishing rate would be correlative to the polishing platforms designs, slurry delivery characteristics, planarization efficiency and overpolish windows. To integrate the relationship and optimize the process windows, this paper will investigate the process comparison and capabilities on various polishing methods and figure out the correlation between polishing methods and process parameters; then in advance simulate these polishing para-

*Corresponding author. Tel.: +886-6-5052000x8069; fax: +886-6-5052081.
E-mail address: ylwang@tsmc.com.tw (Y.L. Wang).

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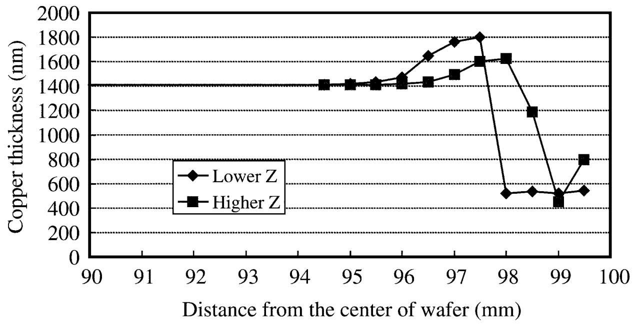

Fig. 1. Copper thickness profile across the edge of the wafer after electroplating process. (Z level means the distance between the cathode and anodic electrodes.)

meters to understand the performance of uniformity and removal rate on various polishing platforms.

2. Description-copper polisher techniques

There are more than two types of commercial CMP platform applied in copper polishing process. By the pad moving direction, they can often split into two major types: one is rotary or oscillation polisher and the other is linear.

In conventional rotary or oscillation CMP platform design, the wafer is located under the carrier film, diaphragm or air-back polishing head; then closely contact to the polishing pad, which is attached above the rigid platen. This design is useful to control consistent removal rate for wafer-to-wafer polishing, due to exist stable contact and provide less variation of slurry film between the wafer and the pad. However, there is a limit capability in non-uniformity and polishing profile control [5]. It is lack of the flexible space to compensate the pad deformation and down-force distribution on the wafer. Hence, many developments focus on the novel air-back carrier [6], multiple-zone backside pressure [7] or in-situ dynamic full-wafer endpoint detection [8]. All wish to provide the tunable polishing profile and improve the control of non-uniformity.

However, linear polisher would relatively provide more flexible uniformity and profile control with the air-bearing platen design [9]. It is due that the design provides the adjustable belt above air-bearing platen to fit the full-wafer surface. However, the floating air-bearing belt also performed less stable removal rate control for wafer to wafer than rotary one. Hence, we try to summarize the process comparison of these platforms in Table 1 and explain the advantage and disadvantage of polishing methods for the endpoint system, uniformity and removal rate control. It will be useful to understand the difference for various polishing methods and optimize the process between plating and polishing.

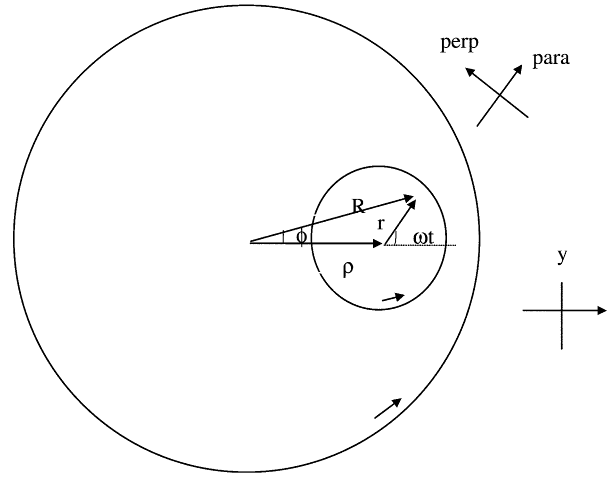

Fig. 2. Platen and wafer configuration for conventional rotary polisher. (Platen and wafer rotate at the same direction.)

3. Simulation for various CMP technique

Although the various CMP platform design applied and required in the process optimization, some common parameters would be adjusted in each approach. These parameters mainly include with down-force, average relative velocity and polishing sweeping trajectory. By the adjustment of these parameters, it is possible to benchmark with different polisher and perform the similar results in the uniformity and removal rate. Hence, the following simulation will calculate the correlation of these parameters and understand the process control in advance.

Table 1
Comparison of process performance in various polishing platform

Platform (polisher)	Removal rate deviation (3σ)	Within-wafer uniformity deviation (1σ)	Endpoint detection	u-scratch defect	Remarks
Rotary or orbital	10–15%	4–8%	Stable	More	Rigid platen to contact the wafer
Linear	20–30%	2–5%	Less stable	Less	More tracking in air-bearing belt

3.1. Rotary polisher

Conventional rotary polisher has a rotating platen and a rotating wafer carrier as shown in Fig. 2. The velocity vector (with respect to the earth) of the point at radius of R on the pad is given by

$$V_x = -\Omega R\sin\phi \qquad V_y = \Omega R\cos\phi \tag{1}$$

where V_x and V_y are the x and y components of the velocity, Ω is the angular velocity of the platen, ϕ is an angle, which is illustrated in Fig. 2.

The relative velocity vector of a point on the pad with respect to wafer is the pad velocity vector in the reference coordinate system, which is fixed on the rotating wafer. Furthermore, the relative velocity vector can be discomposed into two components, one parallel to and the other perpendicular to the radius of the concerned point on the wafer. The parallel component is

$$\begin{aligned} v_{\text{para}} &= V_x\cos(\omega t) + V_y\sin(\omega t) \\ &= -\Omega R\sin\phi\cos(\omega t) + \Omega R\cos\phi\sin(\omega t) \\ &= \Omega R\sin(\omega t - \phi) \\ &= \Omega\rho\sin(\omega t) \end{aligned} \tag{2}$$

where ρ is the distance between the center of the platen and the center of the wafer, ω is the angular velocity of the wafer ration, and t is time. Note that R in Eq. (2) is a variable and its value depends on the rotation angle of the wafer. The perpendicular component of the relative velocity vector is

$$\begin{aligned} v_{\text{perp}} &= -V_x\sin(\omega t) + V_y\cos(\omega t) - \omega r \\ &= \Omega R\sin\phi\sin(\omega t) + \Omega R\cos\phi\cos(\omega t) - \omega r \\ &= \Omega R\cos(\omega t - \phi) - \omega r \\ &= (\Omega - \omega)r + \Omega\rho\cos(\omega t) \end{aligned} \tag{3}$$

The name of modulus of the relative velocity vector will be abbreviated to relative velocity in all following paragraphs for the reason of simplicity. The relative velocity is equal to

$$\begin{aligned} v &= \sqrt{v_{\text{para}}^2 + v_{\text{perp}}^2} \\ &= \sqrt{\Omega^2\rho^2 + (\Omega-\omega)^2 r^2 + 2(\Omega-\omega)\Omega r\rho\cos(\omega t)} \end{aligned} \tag{4}$$

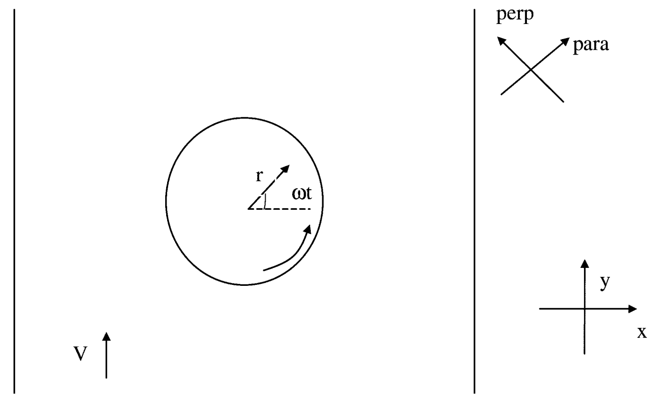

Fig. 3. Belt and wafer configuration for linear polisher. (Wafer rotated on the center of the belt.)

The average of relative velocity over a wafer rotation cycle is given by

$$\begin{aligned} \bar{v}(r) &= \frac{\omega}{2\pi}\int_0^{2\pi/\omega} v\ \mathrm{d}t \\ &= \Omega\rho\left\{\frac{1}{2\pi}\int_0^{2\pi}\sqrt{1+\left(1-\frac{\omega}{\Omega}\right)^2\left(\frac{r}{\rho}\right)^2+2\left(1-\frac{\omega}{\Omega}\right)\frac{r}{\rho}\cos\theta}\ \mathrm{d}\theta\right\} \end{aligned} \tag{5}$$

3.2. Linear polisher

The linear polisher, such as LAM Teres CMP system [9], has a belt, which moves linearly. The illustration and notation are shown on Fig. 3. Hence, the belt velocity vector is

$$V_x = 0 \qquad V_y = V \tag{6}$$

where V is the linear motion speed of the belt.

The parallel component of the relative velocity vector is

$$v_{\text{para}} = V\sin(\omega t) \tag{7}$$

where ω is the angular velocity of wafer rotation.

The perpendicular component of the relative velocity vector is

$$v_{\text{perp}} = V\cos(\omega t) - \omega r \tag{8}$$

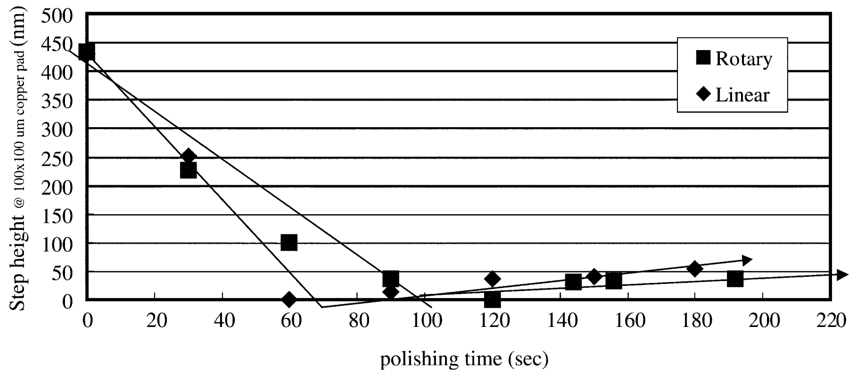

Fig. 4. Comparison of planarization efficiency between rotary and linear polishers. (Step height change measured on the 100×100 μm copper pad.)

The relative velocity is equal to

$$v=\sqrt{v_{\text{para}}^2+v_{\text{perp}}^2}=\sqrt{V^2+\omega^2r^2-2V\omega r\cos(\omega t)} \quad (9)$$

Using Eq. (8), the average relative velocity over a wafer rotation cycle is given by

$$\bar{v}=\frac{\omega}{2\pi}\int_0^{2\pi/\omega}v\ \mathrm{d}t=V\left\{\frac{1}{2\pi}\int_0^{2\pi}\sqrt{1+\left(\frac{\omega r}{V}\right)^2-2\frac{\omega r}{V}\cos\theta}\quad \mathrm{d}\theta\right\} \quad (10)$$

Assumed the polishing processes obey the Preston's law, the correlations between polishing profile and the average velocity (the removal rate, too) are calculated by the Eqs. (5) and (10), responded to the rotary and linear polisher, respectively. The correlation can figure out the difference of the uniformity between various polishers. Besides, in the rotary polisher, the distance from the center of platen to the center of wafer would be applied with different carrier sweeping trajectory, such as usual simple harmonic motion (SHM) or sinusoid oscillation. Thus, it can change the uniformity and polishing profile from the parameters tuning to achieve the optimization from polishing profile to plating profile on the copper films.

4. Experiments

All experiments are carrier out on the 8 inch wafers. For the blanket wafer with copper film, they are polished in the example of rotary polisher, AMAT Mirra-Mesa CMP, and in the linear polisher, LAM Teres CMP. These polishers would be applied with the same slurry and conditioners. In addition, a four-point probe tool, Tencor Rs-75 can be used to measure the removal rate and uniformity. The step height changes during polishing are measured on the 100×100 μm copper pad by the alpha-step profiler. The planarization efficiency is calculated by the difference between the initial step height and the minimum of step height over the polishing time.

5. Results

Beyond the comparison between various polisher, shown on Table 1, the planarization efficiency has been done in the Fig. 4. The data show that the planarization rate (namely, the ratio of the pattern step height reduction to polishing time) on linear polisher is slightly faster than on the rotary one before the lowest step height reached. Besides, the planarization rate is positively dependent on the local removal rate [10] (therefore, the local relative velocity too, if polishing obey Preston's law.) From the Eqs. (4) and (8), the ratio of the relative velocity of linear to rotary polishers would be greater than 1 on the assumption of V being equal to $\Omega\rho$ and Ω close to ω, (i.e. assumed linear belt speed = platen's rotary speed and platen's angular velocity = wafer's angular velocity). That is, the belt of linear polisher seems to perform more rigid pad deformation and slightly faster relative velocity across the local area of the wafer than the platen of rotary polisher. Therefore, the planarization efficiency of linear polisher is better than ones of rotary polisher [10].

In order to realize the difference between various platforms, we take the advantage of the Eqs. (5) and (10) to simulate the profiles of the average velocity across the radius of wafer for rotary and linear polisher, shown in Fig. 5. (It is same meaning for the profile of removal rate if the process also obeys the Preston's law.) From the simulation results, it shows the velocity profile changing with various polishing sweep trajectories in the rotary polisher. The sweeping trajectories are

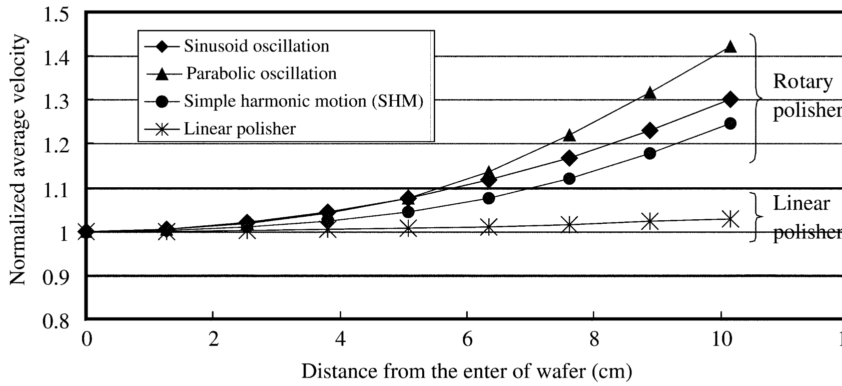

Fig. 5. The relationship between normalized average relative velocity profile and the distance from the center of wafer for various polisher and sweeping trajectory in rotary polishers. (Therefore, removal rate too if the polishing obey the Preston's law.)

just usual examples applied in the copper CMP system. All are illustrated in Fig. 6. That replies the uniformity of rotary polishers would be worse than the linear ones. Of course, the uniformity control is also changed by the various polishing sweeping trajectories. For example, the thickness profile of the electroplating, like the result of Fig. 1, would be suit to polish with the parabolic sweeping trajectory. It can achieve the faster removal rate in the wafer edge and perform the better uniformity and process optimizations between plating and polishing. Besides, if the plating profile of Fig. 1 is polished in the linear polisher, it is easy to suffer the copper remaining on the edge of the wafer, due to the more flat profile in the linear polisher, shown in the Fig. 5. Hence, the development of the extra air-zone force would be applied and designed under the edge of the belt [9].

Sometimes the simulation equations can explain and calculate the correlations of mechanic parameters between rotary and linear polishers. For instance of 8 inch polishers, if the value of linear belt speed (V) is setting three times than the value of angular velocity (Ω) of rotary platen, there is the same removal rate performed in both platforms. Besides, the carrier rotation speed is less impact on the uniformity, while the belt speed is greather than the carrier rotation speed (i.e. $V \gg \omega r$) in the linear polisher or while the angular velocity (Ω) of rotary platen is close to the angular velocity of the carrier. All of these correlations would clearly figure out the characteristics of various polishers in polishing profile and uniformity control.

6. Conclusions

In this study, rotary and linear polishers are used as the main polishing platforms in copper CMP process. On the difference of mechanical designs in both polishers, there is more stable removal rate in the rotary polisher, but better uniformity control in the linear polishers. It is due to the rigid contact and support between wafer and the pad for the rotary polisher and flexible motion of the linear belt and air-bearing platen across the wafer for the linear polisher. Besides, from the simulation Eqs. (5) and (10), the local relative velocity of the linear polisher is larger than one of the

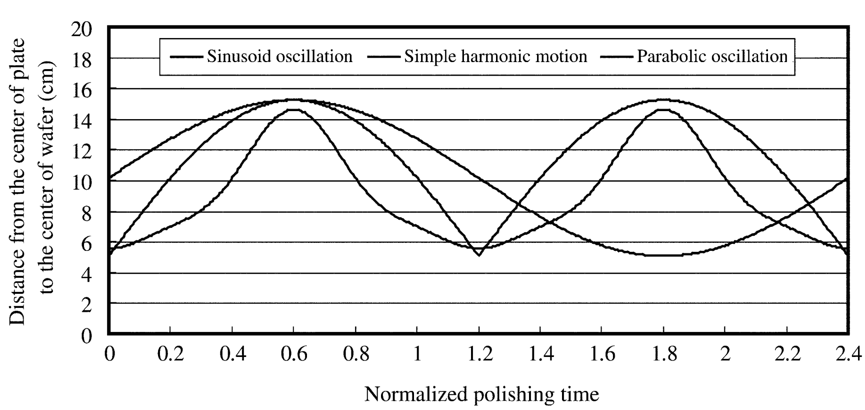

Fig. 6. The various sweeping trajectories of polishing carrier in the rotary polishers. (Some of the data in Fig. 5 is calculated from these trajectories.)

rotary polisher. Hence, in the planarization efficiency, the linear polisher is better than the rotary one.

In addition, simulation equation of linear and rotary polishers can explain the difference of profile and uniformity control. By various sweeping trajectories of polishing carrier on the rotary polisher, the optimized polishing profile can totally resolve the thicker copper thickness issue on the wafer edge from the non-uniformity of the electric field distribution on the electroplating process.

Finally, the mechanic parameters in the simulation equations are not only the factors on the uniformity and polishing profile, but other factors, such as slurry effects, pad deformation and conditioner wearing, also affect the removal rate and uniformity performance. Hence, under the understanding of these simulation parameters on various polishing platforms, it is useful to distinguish the difference between mechanical designs of polishers and the effects of consumable parts and judge the evaluation of the polishers in the optimization of copper process.

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