Model analysis and experimental investigation of the friction torque during the CMP process*

Guo Dongming(郭东明), Xu Chi(徐驰)†, Kang Renke(康仁科), and Jin Zhuji(金洙吉)

Key Laboratory for Precision and Non-Traditional Machining Technology of Ministry of Education, Dalian University of Technology, Dalian 116024, China

Abstract: A model for calculating friction torque during the chemical mechanical polishing (CMP) process is presented, and the friction force and torque detection experiments during the CMP process are carried out to verify the model. The results show that the model can well describe the feature of friction torque during CMP processing. The research results provide a theoretical foundation for the CMP endpoint detection method based on the change of the torque of the polishing head rotational spindle.

Key words: CMP; friction torque; endpoint detection

DOI: 10.1088/1674-4926/32/3/036002 **EEACC:** 2570

1. Introduction

Chemical mechanical polishing (CMP) as a critical technology in the ULSI manufacturing process has been extensively employed to achieve global planarization of the bare or patterned wafer. However, during formation of the multilayer Cu interconnection structure, over-polishing (removing too much) and under-polishing (removing too little) often occur when removing the excess materials using CMP. Over-polishing results in excessive copper dishing and dielectric erosion, causing the degradation of device performance or yield; under-polishing means that the process needs to be repeated, leading to an increase in IC fabrication cost. Therefore, the fast, accurate and reliable endpoint detection (that is to determine when to stop CMP) is a key piece of technology to assure the quality of CMP processing and improve the yield and efficiency. Among many CMP endpoint detection methods, the frictional endpoint detection methods are representative for the Cu CMP process[1−3]. The frictional endpoint detection methods judge the CMP endpoint by detecting the change in the friction coefficient, torque or motor current during the CMP process. Some research on the influence of the relative speed between the wafer and the polishing pad on the friction coefficient during the CMP process has been done[4]. However, studies of the feature of friction torque during the CMP process are still limited. Yi investigated the feature of friction torque during the CMP process using a linear CMP system[5, 6]. However, for the widely used rotary CMP process, there have been few studies of the feature of friction torque during the CMP process.

In this paper, a model for calculating the friction torque during the CMP process is presented, and friction force and torque detection experiments during the CMP process were carried out to verify the model.

2. Modeling

The kinematic and relative speed relationship between the wafer and the polishing pad during the CMP process are shown in Fig. 1. In this paper, the factor of the oscillation of the polishing head is ignored, because the oscillation speed of the polishing head is very slow with respect to the relative speed between the wafer and the polishing pad, and it has little influence on the friction force during the CMP process[7]. Figure 1(a) is a schematic diagram of the kinematic relationship between the wafer and the polishing pad. O_p and O_w are, respectively, the center of the polishing pad and the wafer; ω_p and ω_w are, respectively, the value of the angular speed of the polishing pad and the wafer; point A is a point on the wafer surface; r_i and r_j are, respectively, the distance from point A to O_w and O_p; e is the distance between O_p and O_w. Figure 1(b) is a schematic diagram of the relative velocity of point A with respect to the corresponding point on the polishing pad. $\boldsymbol{v}_\mathrm{w}$ and $\boldsymbol{v}_\mathrm{p}$ are, respectively, the velocity of point A and the corresponding point on the polishing pad; $\boldsymbol{v}$ is the relative velocity of point A with respect to the corresponding point on the polishing pad, and v is its value; $\boldsymbol{v}_\mathrm{x}$, $\boldsymbol{v}_\mathrm{y}$ and $\boldsymbol{v}_\mathrm{t}$ are, respectively, $\boldsymbol{v}$ in the x, y and tangential directions. The relative velocity $\boldsymbol{v}$ can be calculated as follows,

$$\boldsymbol{v} = \boldsymbol{v}_\mathrm{w} - \boldsymbol{v}_\mathrm{p}. \tag{1}$$

Based on the geometrical relationship, $\boldsymbol{v}_\mathrm{x}$, $\boldsymbol{v}_\mathrm{y}$ and $\boldsymbol{v}_\mathrm{t}$ can be obtained as follows,

$$\boldsymbol{v}_\mathrm{x} = (\omega_\mathrm{p} - \omega_\mathrm{w}) r_\mathrm{i} \sin\theta, \tag{2}$$

$$\boldsymbol{v}_\mathrm{y} = (\omega_\mathrm{w} - \omega_\mathrm{p}) r_\mathrm{i} \cos\theta + \omega_\mathrm{p} e, \tag{3}$$

$$\boldsymbol{v}_\mathrm{t} = (\omega_\mathrm{w} - \omega_\mathrm{p}) r_\mathrm{i} + \omega_\mathrm{p} e \cos\theta. \tag{4}$$

* Project supported by the Joint Fund of NSFC with Guangdong Province, China (No. U0734008) and the National Science and Technology Major Project of China (No. 2009ZX02011).

† Corresponding author. Email: xuchi_dut@163.com

Received 9 August 2010, revised manuscript received 27 September 2010

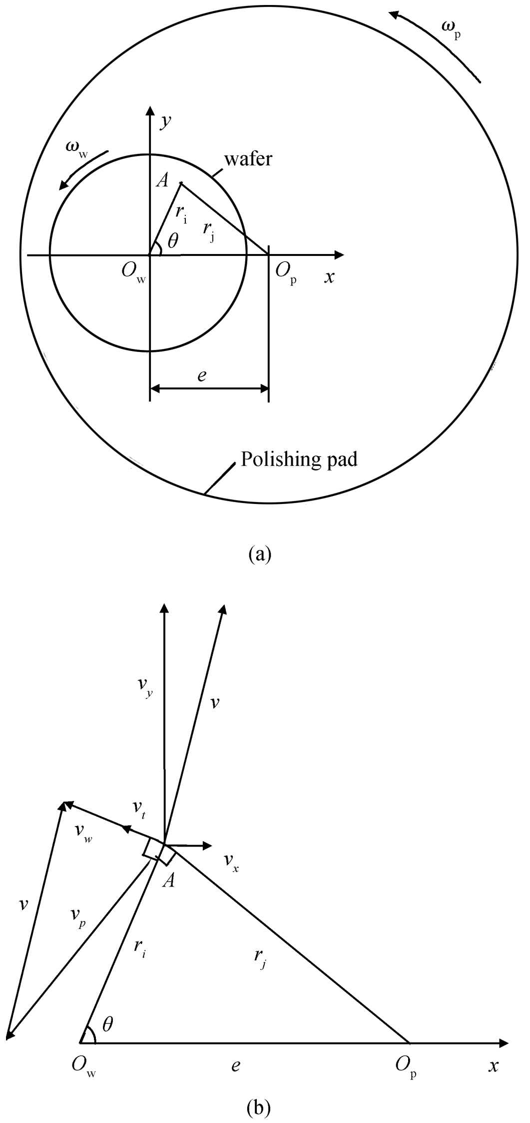

Fig. 1. (a) Schematic diagram of the kinematic relationship between the wafer and the polishing pad. (b) Relative speed of point A on the wafer surface with respect to the corresponding point on the polishing pad.

The value of relative velocity v can be calculated as follows,

$$v = \sqrt{v_x^2 + v_y^2} = \sqrt{(\omega_w - \omega_p)^2 r_i^2 + \omega_p^2 e^2 + 2(\omega_w - \omega_p)\omega_p e r_i \cos\theta}. \quad (5)$$

The value of the friction force $\delta \boldsymbol{F}$ between dS and the polishing pad and the friction torque $\delta \boldsymbol{M}$ generated by dS with respect to O_w during the CMP process can be calculated as follows,

$$\delta \boldsymbol{F} = \mu P \mathrm{d}S, \quad (6)$$

$$\delta \boldsymbol{M} = \boldsymbol{r}_i \times \delta \boldsymbol{F}, \quad (7)$$

where dS is an infinitesimal area on the wafer surface, and the distance from dS to the center of the wafer surface is r_i; P is the average polishing pressure of every point on the wafer surface; and μ is the friction coefficient.

During the CMP process, in an infinitesimal area, the contact state of the wafer and the polishing pad might be direct contact or non-contact. The Stribeck friction model is a widely used friction model, and it can well describe the friction characteristic in the different contact states. Therefore, the Stribeck friction model is used to describe the friction coefficient between the wafer and the polishing pad. Based on the Stribeck friction model, the friction coefficient μ can be written as

$$\mu = \mu_c + (\mu_s - \mu_c)e^{-v/v_s} + \sigma v, \quad (8)$$

where μ_c is the Coulomb friction coefficient; μ_s is the maximum static friction coefficient; v_s is the Stribeck velocity; and σ is the viscosity coefficient.

For the usual CMP processing parameters, the change range of ω_w and ω_p is not big; that is, the change range of the relative speed of every point on the wafer surface with respect to the corresponding point on the polishing pad is not big. Therefore, in order to simplify the calculation model, the friction coefficient μ is approximated as follows,

$$\begin{aligned}\mu &\approx \mu_c + (\mu_s - \mu_c)(B - Kv/v_s) + \sigma v \\ &= B\mu_s + (1 - B)\mu_c - \frac{Kv(\mu_s - \mu_c)}{v_s} + \sigma v,\end{aligned} \quad (9)$$

where K and B are the parameters.

Assume that the polishing pressure of every point on the wafer surface is equal, based on Eqs. (6) and (7), noting that the direction of the friction force is always opposite to that of the relative speed during the CMP process, the total friction force $\boldsymbol{F}$ and friction torque $\boldsymbol{M}$ during the CMP process can be calculated as

$$\boldsymbol{F} = -\int_0^R \int_0^{2\pi} \frac{\boldsymbol{v}}{v} \mu P r_i \mathrm{d}\theta d r_i, \quad (10)$$

$$\boldsymbol{M} = -\int_0^R \int_0^{2\pi} \frac{\boldsymbol{v}_t}{v} \mu P r_i^2 \mathrm{d}\theta d r_i. \quad (11)$$

Based on Eqs. (2)–(4), (9)–(11), the friction force $\boldsymbol{F}$ in the x, y direction $\boldsymbol{F}_x$, $\boldsymbol{F}_y$ and the friction torque $\boldsymbol{M}$ can be written as

$$\boldsymbol{F}_x \approx -\int_0^R \int_0^{2\pi} \left(k + \frac{b}{v}\right)(\omega_p - \omega_w) r_i \sin\theta P r_i \mathrm{d}\theta \mathrm{d}r_i, \quad (12)$$

$$\boldsymbol{F}_y \approx -\int_0^R \int_0^{2\pi} \left(k + \frac{b}{v}\right)[(\omega_w - \omega_p) r_i \cos\theta + \omega_p e] P r_i \mathrm{d}\theta \mathrm{d}r_i, \quad (13)$$

$$\boldsymbol{M} \approx -\int_0^R \int_0^{2\pi} \left(k + \frac{b}{v}\right)[(\omega_w - \omega_p) r_i + \omega_p e \cos\theta] P r_i^2 \mathrm{d}\theta \mathrm{d}r_i, \quad (14)$$

where $k = \sigma - \dfrac{K(\mu_s - \mu_c)}{v_s}$, $b = B\mu_s + (1 - B)\mu_c$.

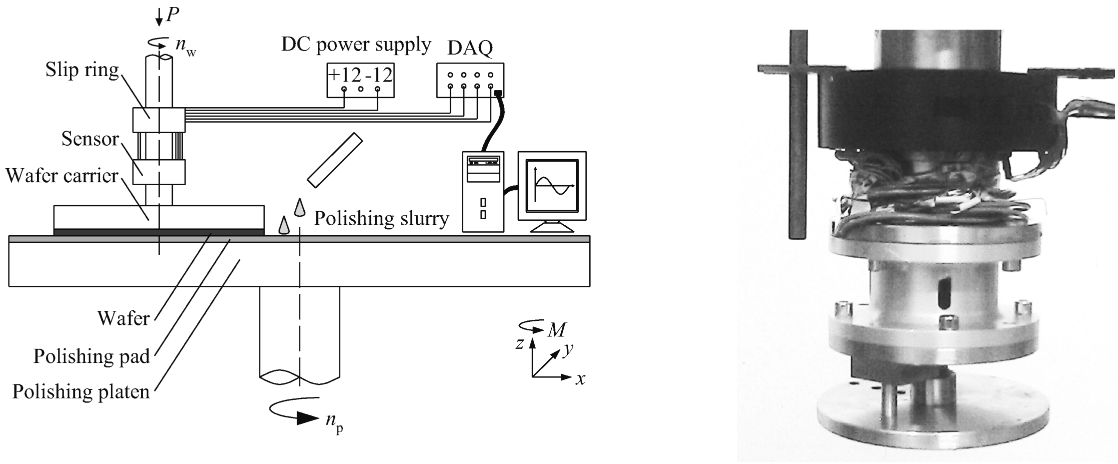

Fig. 2. (a) Schematic diagram of the CMP endpoint detection system. (b) Photo of the polishing head.

Because during the CMP process ω_p and ω_w are very close, based on Eq. (5) the value of relative speed v can be approximated as

$$v \approx \omega_p e. \tag{15}$$

Using Eq. (15), the calculated results of $\boldsymbol{F}_x$, $\boldsymbol{F}_y$ and $\boldsymbol{M}$ can be obtained as

$$\boldsymbol{F}_x = 0, \tag{16}$$

$$\boldsymbol{F}_y \approx -(k\omega_p e + b)P\pi R^2, \tag{17}$$

$$\boldsymbol{M} \approx \frac{1}{2}P\pi R^4(\omega_p - \omega_w)(k + \frac{b}{\omega_p e}), \tag{18}$$

where R is the radius of the wafer.

From Eq. (18), it can be seen that the friction torque will be equal to zero when the angular speed of the wafer and the polishing pad is equal. However, the calculation result is on the assumption that the polishing pressure of every point on the wafer surface is equal. During the practical CMP process, the polishing pressure of every point on the wafer surface will not be equal exactly because of the influence of all kinds of factors. Therefore, assume that the average polishing pressure of every point on the left half and right half of the wafer surface shown in Fig. 1(a) is, respectively, P_1 and P_2, the corrected friction torque $\boldsymbol{M}_m$ is as follows,

$$\boldsymbol{M}_m \approx \boldsymbol{M} + \frac{2}{3}\Delta P R^3(k\omega_p e + b), \tag{19}$$

where $\Delta P = P_1 - P_2$.

From Eqs. (12)–(14), it can be seen that the influence of the non-uniformity of the polishing pressure on the friction force is far less than its influence on the friction torque when ω_p and ω_w are very close, so the influence of the non-uniformity of the polishing pressure on the friction force is ignored. Based on Eqs. (16) and (17), the value of the friction force F can be obtained as

$$F \approx (k\omega_p e + b)P\pi R^2. \tag{20}$$

Using Eqs. (19) and (20), the corrected friction torque $\boldsymbol{M}_m$ can be written as

$$\boldsymbol{M}_m \approx \frac{1}{2e}FR^2(1 - \frac{\omega_w}{\omega_p}) + \frac{2}{3\pi}FR\frac{\Delta P}{P}. \tag{21}$$

Assume that the relationship of $\frac{\Delta P}{P}$ and $\frac{\omega_p}{\omega_w}$ is

$$\frac{\Delta P}{P} = \eta\left(\frac{\omega_w}{\omega_p}\right)^2 + \lambda\frac{\omega_w}{\omega_p} + \gamma, \tag{22}$$

where η, λ and γ are the model parameters, and they can be determined using the least squares estimation based on the measured friction torque and the friction force at different processing parameters.

From Eq. (21), it can be seen that the relationship between the friction torque and the angular speed of the polishing pad is very complex. However, based on the calculation result of Eq. (21), the following conclusions can be drawn: if ΔP is not equal to zero, the friction torque during the CMP process will not be zero even when the angular speed of the wafer and the polishing pad is equal (the relative speed of every point on the wafer surface with respect to the polishing pad is equal); the direction of the friction torque will not change under the usual CMP processing parameters ($\omega_p \geqslant \omega_w$) if ΔP is positive.

3. Experiments

To verify the model, the friction force and torque detection experiments were carried out using a developed CMP endpoint detection system, as shown in Fig. 2. The wafer is fixed on a stainless steel platen, and the platen is connected to a specially designed three-axis force and z-axis torque sensor by a ball joint. The friction force, downforce and torque during the CMP process can be measured by the sensor connected to the polishing head rotational spindle. Because both the polishing platen and the polishing head are rotational during the CMP process, the sensor power supply and the measured electrical signals are transmitted by a precision slip ring mounted concentrically on the polishing head rotational spindle. Then the measured signals are sent to the computer by a 16 bit simultaneous data acquisition instrument.

The sensor can measure the force in its x, y, z direction and z-axis torque. The measured z direction force is the downforce; the measured z-axis torque is the torque of the polishing head rotational spindle, that is the friction torque during

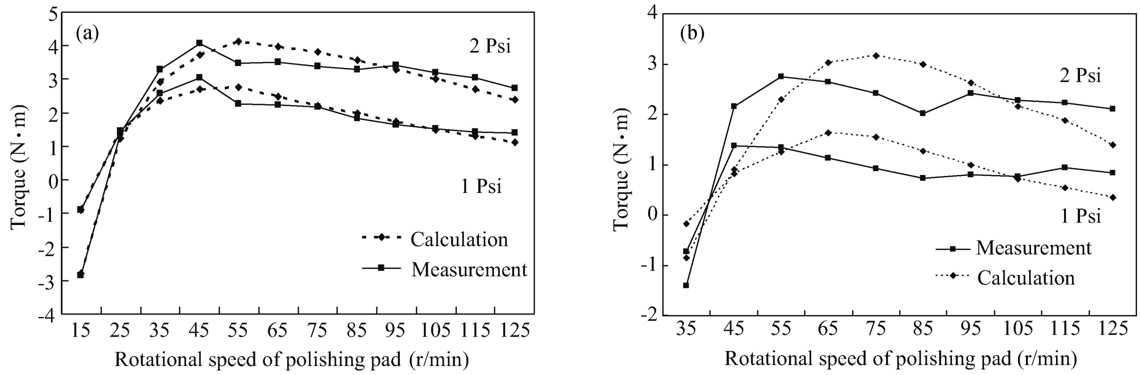

Fig. 3. Torque during the CMP process. (a) Cu wafer. (b) Silicon wafer.

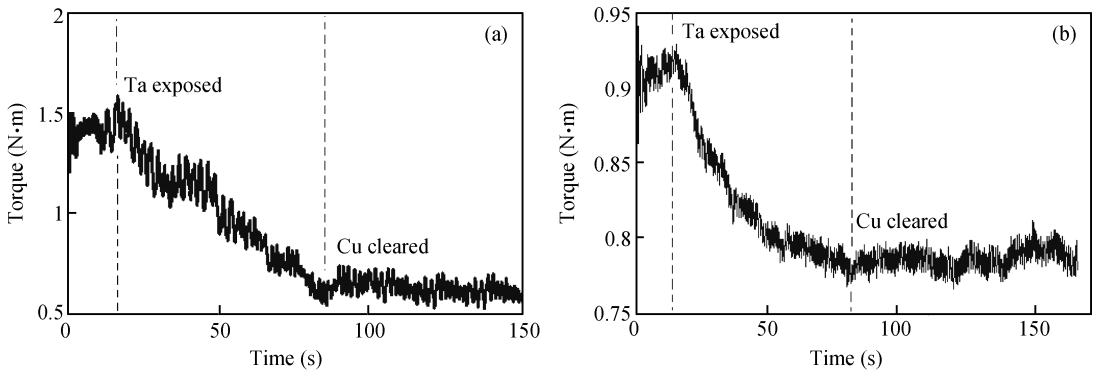

Fig. 4. Torque during Cu CMP process. (a) ω_p = 85 r/min. (b) ω_p = 105 r/min.

the CMP process. The value of the friction force between the wafer and the pad during the CMP process can be calculated with the following formula,

$$F = \sqrt{F_x^2 + F_y^2}, \tag{23}$$

where F_x and F_y are the measured force in the sensor's x and y direction.

4. Results and discussion

Figure 3 shows the friction torque during the Cu and silicon wafer CMP process. The experimental conditions were as follows. The flow of polishing slurry was 150 ml/min; the rotational speed of the polishing head was 85 r/min; the diameter of both the Cu and the silicon wafers was 150 mm; the polishing pad was not conditioned because the used time was only about 20 min; the polishing head was not swing. Figure 3(a) shows the friction torque during the Cu wafer CMP process. The surface roughness of the Cu wafer was 57 nm; Cabot iCue 5001 polishing slurry and polyurethane polishing pad were used. Figure 3(b) shows the friction torque during the silicon wafer CMP process. The surface roughness of the silicon wafer was 5 nm; the Cabot SS 12 polishing slurry and velvet polishing pad were used. The data of the friction torque was the average of all measured data in a period of time, and the data in the same processing parameters was measured three times. It can be seen that the value of the calculation is in close accordance with the value of measurement. Just like the calculation results of Eq. (21), because the relationship of the friction torque and the angular speed of polishing pad is very complex, the change trend of the friction torque is uncertain. However, neither the friction torque during the Cu wafer CMP process nor the friction torque during the silicon wafer CMP process is equal to zero when the rotational speed of the polishing head and the polishing platen is equal, and the direction of the friction torque does not change under the usual CMP processing parameters ($\omega_p \geqslant \omega_w$).

Figure 4 shows the change in the friction torque during the Cu CMP process. The experimental conditions were as follows. Cabot iCue 5001 polishing slurry and polyurethane polishing pad were used; the polished workpiece was a tantalum (Ta) wafer on whose surface a Cu layer was electroplated; the rotational speed of the polishing head was 85 r/min; the downforce was 2 Psi. It can be seen that the change in the friction torque is clear when the polished material transits from Cu to Ta. Just as the feature of the friction torque during the Cu wafer and the silicon wafer CMP process, the friction torque is not equal to zero even when the rotational speed of the polishing head and the polishing platen is equal, and the direction of the friction torque does not change under the usual CMP processing parameters ($\omega_p \geqslant \omega_w$).

From Figs. 3 and 4, it can be seen that the friction torque is not equal to zero even when the rotational speed of the polishing head and the polishing platen is equal, and the direction of the friction torque does not change under the usual CMP processing parameters ($\omega_p \geqslant \omega_w$). The results indicate that the CMP endpoint detection method based on the change in the torque of polishing head rotational spindle is feasible for the Cu CMP process.

5. Conclusion

A model for calculating the friction torque during the CMP process was presented. The friction force and torque detection experiments during the CMP process were carried out to verify the model. The results show that the friction torque calculation model can well describe the feature of the friction torque during the CMP process, and the value of the calculation is well in accordance with the value of measurement. The research results can provide a theoretical foundation for the CMP endpoint detection method based on the change of the torque of the polishing head rotational spindle.

References

[1] Bibby T, Holland K. Endpoint detection for CMP. J Electron Mater, 1998, 27(10): 1073

[2] Jeong H, Kim H, Lee S, et al. Multi-sensor monitoring system in chemical mechanical planarization (CMP) for correlations with process issues. Ann CIRP, 2006, 55(1): 325

[3] Hocheng H, Huang Y L. A comprehensive review of endpoint detection in chemical mechanical planarization for deep-submicron integrated circuits manufacturing. Int J Mater Product Tech, 2003, 18(4–6): 469

[4] Jia Zhenyuan, Su Jianxiu, Jin Zhuji, et al. Friction characteristic of wafer surface in chemical mechanical polishing. Key Eng Mater, 2005, 291/292: 389

[5] Yi J. On the wafer/pad friction of chemical-mechanical planarization (CMP) processes—part I: modeling and analysis. IEEE Trans Semicond Manuf, 2005, 18(3): 359

[6] Yi J. On the wafer/pad friction of chemical-mechanical planarization (CMP) processes—part II: experiments and applications. IEEE Trans Semicond Manuf, 2005, 18(3): 371

[7] Su Jianxiu. Study on material removal mechanism of chemical mechanical polishing in IC manufacturing. Dalian: Dalian University of Technology, 2006