Experimental and Numerical Analysis of A Novel Ceria Based Abrasive Slurry for Interlayer Dielectric Chemical Mechanical Planarization

Yun Zhuang[a], Leonard Borucki, and Ara Philipossian
Araca Incorporated, 6655 North Canyon Crest Drive, Suite 1205, Tucson, Arizona 85750, USA

Eric Dien, Mohamed Ennahali, George Michel, and Bernard Laborie
Kemesys, ZI Le Verdalai - CD 6, 13790 Peynier, France

Yun Zhuang, Manish Keswani, Daniel Rosales-Yeomans, Hyosang Lee, and Ara Philipossian
Department of Chemical and Environmental Engineering, University of Arizona, Tucson, Arizona 85721, USA

[a]Email : yunzhuang@comcast.net

(Received February 9 2006, Accepted May 22 2006)

In this study, a novel slurry containing ceria as the abrasive particles was analyzed in terms of its frictional, thermal and kinetic attributes for interlayer dielectric (ILD) CMP application. The novel slurry was used to polish 200-mm blanket ILD wafers on an IC1000^{TM} K-groove pad with in-situ conditioning. Polishing pressures ranged from 1 to 5 PSI and the sliding velocity ranged from 0.5 to 1.5 m/s. Shear force and pad temperature were measured in real time during the polishing process. The frictional analysis indicated that boundary lubrication was the dominant tribological mechanism. The measured average pad leading edge temperature increased from 26.4 to 38.4 °C with the increase in polishing power. The ILD removal rate also increased with the polishing power, ranging from 400 to 4000 A/min. The ILD removal rate deviated from Prestonian behavior at the highest $p \times V$ polishing condition and exhibited a strong correlation with the measured average pad leading edge temperature. A modified two-step Langmuir-Hinshelwood kinetic model was used to simulate the ILD removal rate. In this model, transient flash heating temperature is assumed to dominate the chemical reaction temperature. The model successfully captured the variable removal rate behavior at the highest $p \times V$ polishing condition and indicates that the polishing process was mechanical limited in the low $p \times V$ polishing region and became chemically and mechanically balanced with increasing polishing power.

Keywords : Ceria abrasive slurry, ILD chemical mechanical planarization, Shear force, Langmuir-Hinshelwood model

1. INTRODUCTION

Recently, cerium dioxide (ceria) particles have been used as the slurry abrasive for shallow trench isolation (STI) CMP applications due to the superior oxide-to-nitride removal rate selectivity[1]. In this study, a novel slurry containing ceria abrasive particles was analyzed in terms of its frictional, thermal and kinetic attributes for ILD CMP processing. The slurry was used to polish blanket 200-mm ILD wafers on an IC1000^{TM} K-groove pad with in-situ conditioning under different polishing pressures and sliding velocities. Shear force was measured in real time to determine the coefficient of friction and tribological mechanism for the process. Pad temperature was also monitored in real time to determine the thermal attribute of the process. A modified two-step Langmuir-Hinshelwood kinetic model was used to simulate the ILD removal rate, using the transient flash heating temperature as the mean wafer surface chemical reaction temperature. The model also simulated the chemical and mechanical action dominance in the studied polishing region.

2. EXPERIMENTAL

All polishing experiments were performed on a 200-mm Fujikoshi polisher, which has the ability to acquire real-time shear force data critical for determining the coefficient of friction (COF) and lubrication mechanism. The novel slurry was provided by Kemesys (Peynier, France) and used ceria as the abrasive. The average abrasive particle size was about 80 nm and the abrasive concentration in the slurry was 2 % (weight percent). The slurry pH was 8. The slurry was used to polish 200-mm blanket ILD wafers on an IC1000^{TM} K-groove pad with a Suba IV subpad. The ILD wafer surface film consisted of about 2 μm thermally grown silicon dioxide. The ILD film thickness was measured before and after polishing by a Gaertner LES-WS reflectometer to determine the ILD removal rate.

Prior to wafer polishing, the pad was conditioned at 0.4 PSI (2.76 kPa) for 30 minutes using deionized (DI) water with a 4-inch 100-grit Mitsubishi Materials Corporation diamond conditioner. The diamond conditioner rotated at 30 RPM and oscillated at 0.33 Hz. After the 30-minute pad break-in procedure, a silicon wafer was polished with the ceria abrasive slurry at 3 PSI (20.7 KPa) and 1.2 m/s for 10 minutes. The slurry flow rate was kept constant at 250 ml/min. During the silicon wafer polishing, the shear force was measured in real time to insure that stable values were achieved prior to ILD wafer polishing. The same diamond conditioner rotational velocity, oscillation frequency, and conditioning pressure were used for in-situ pad conditioning during the silicon wafer polishing. After the 10-minute silicon wafer polishing, 200-mm blanket ILD wafers were polished at 3 polishing pressures (1, 3 and 5 PSI) and 2 sliding velocities (0.5 and 1.5 m/s) with in-situ pad conditioning. The slurry flow rate, diamond conditioner rotational velocity and oscillation frequency, and conditioning pressure remained unchanged. An Agema 550 infrared thermal imaging camera was used to measure the pad temperature during polishing. The infrared camera took 3 thermal images every second with an accuracy of 0.1 °C. Each ILD wafer was polished for 2 minutes. Two or three ILD wafers were polished at each polishing condition to confirm the experimental reproducibility.

3. POLISHING RESULTS

Figure 1 shows the average coefficient of friction (COF) measured at different polishing conditions. 1,000 shear force data were collected every second during polishing. The values were averaged and divided by the applied normal force to obtain the average COF. The measured average COF fluctuates between 0.27 and 0.59 at different pseudo Sommerfeld numbers (*V/p*). This indicates that boundary lubrication is the dominant tribological mechanism in this study, where the pad surface, the ceria abrasive particles and the wafer surface are all in intimate contact with one another[2].

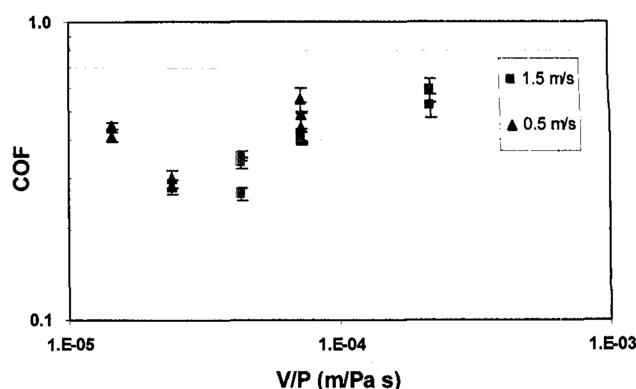

Fig. 1. Average coefficient of friction vs. pseudo Sommerfeld number V/p.

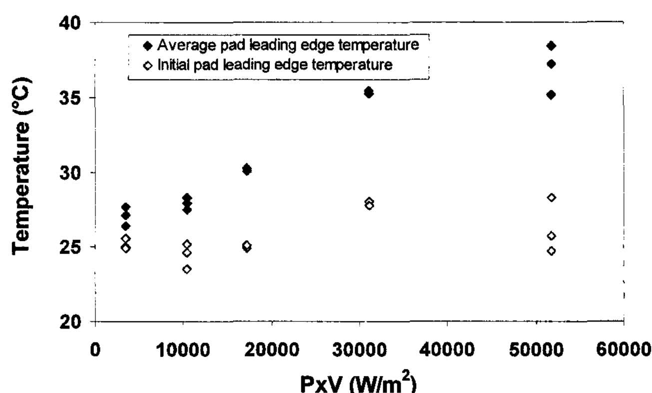

Fig. 2. Pad leading edge temperature measured at different polishing conditions.

Figure 2 shows the pad leading edge temperature measured at different polishing conditions. The average pad leading edge temperature generally increases with the polishing power (*pxV*) as expected. The initial pad leading edge temperature (*i.e*, the pad temperature at the start of the polishing) is also shown in Fig. 2. The observed difference in the average pad leading edge temperature at the same polishing condition is mainly due to their different initial values. Therefore, the pad temperature transient, calculated by subtracting the initial pad temperature from its average value, is very consistent at each polishing condition.

Figure 3 shows the ILD removal rate measured at different polishing conditions. The removal rate appears to increase linearly with the polishing power (*pxV*) when the *pxV* value is less than 31,000 W/m^2. However, the removal rate deviates from Prestonian (linear) behavior at the highest *pxV* condition (51,700 W/m^2). In addition, the removal rate exhibits a strong dependence on the measured average pad leading edge temperature at this polishing condition. A higher average pad leading edge temperature causes a higher wafer surface reaction temperature, leading to a higher removal rate.

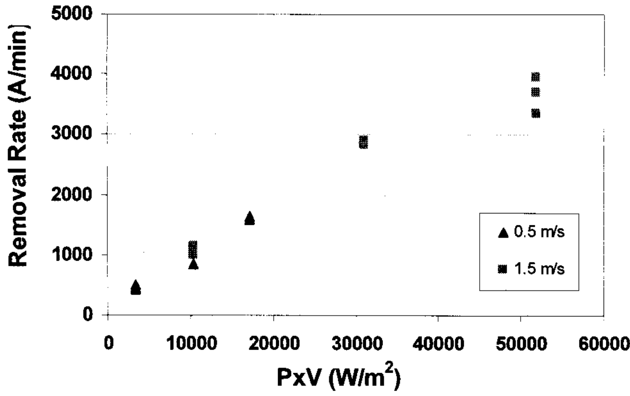

Fig. 3. Measured removal rates.

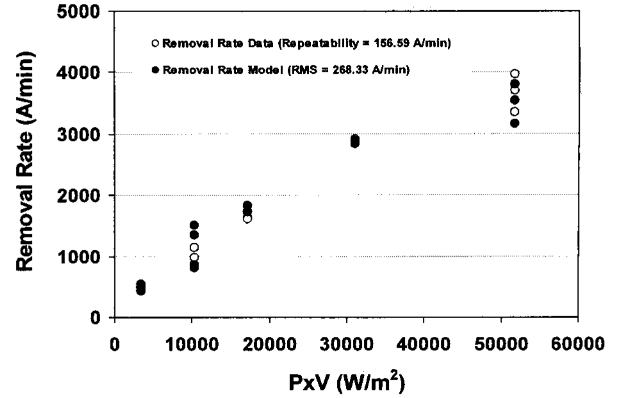

Fig. 4. Comparison of simulated rates (solid symbols) and measured rates.

4. MODELING ANALYSIS

A modified two-step Langmuir-Hinshelwood kinetic model was used to analyze the measured ILD removal rates. In this model, it is assumed that n moles of reactant R in the slurry react with the ILD wafer surface film (S) at rate k_1 to form a surface layer $\underline{L}$,

$$S + nR \xrightarrow{k_1} \underline{L} \quad (3)$$

This surface layer is then removed by mechanical abrasion with rate k_2

$$\underline{L} \xrightarrow{k_2} L \quad (4)$$

The abraded material L is assumed to be carried away by the slurry and not re-deposited on the wafer surface. Assuming the rate of the surface layer formation is equal to the rate of its depletion, the local removal rate in this sequential mechanism is

$$RR = \frac{M_w}{\rho} \frac{k_1 C_R^n}{1 + \frac{k_1 C_R^n}{k_2}} \quad (5)$$

where C_R is the local molar concentration of the reactant R. To simplify the model, it is assumed that there is no reactant depletion so that C_R remains constant in Equation (5). This allows C_R to be absorbed into k_1 and its value effectively set to unity. The chemical reaction rate constant k_1 in Equation (5) is expressed as

$$k_1 = A\exp(-E/kT) \quad (6)$$

where A is an exponential factor, E is the activation energy, k is Boltzman's constant (8.62e-5 eV/K), and T is the reaction temperature. The mechanical removal rate constant k_2 in Equation (5) is expressed as

$$k_2 = C_p \mu_k pV \quad (7)$$

where C_p is an assumed proportionality constant and μ_k is the measured average COF. Assuming the chemical reaction temperature is dominated by transient flash heating, the reaction temperature T in Equation (6) is expressed as

$$T = T_p + \beta \mu_k pV^{1-a} \quad (8)$$

where T_p is the measured average pad leading edge temperature, β is a grouping of parameters including pad thermal properties, and a is an exponent related to the velocity dependence of lubricated frictional heat transfer to the pad. The derivation of Equation (8) is described in detail elsewhere[3]. During model simulation, parameters A, C_p, β and a are optimized to minimize the root mean square error (RMS error) associated with the experimental and predicted values of the removal rates. The activation energy (E) is extracted from the three runs at the highest $p \times V$ polishing condition (51,700 W/m^2), where the polishing is assumed to be more chemically limited compared with the low $p \times V$ polishing region. A value of 0.43 eV is used in the simulation.

Figure 4 compares the simulated and experimental removal rates. The simulated removal rates agree very well with the experimental data. The model successfully captures the non-Prestonian behavior and the variation at the highest $p \times V$ polishing condition.

Figure 5 shows the simulated range of the wafer surface reaction temperature at different polishing conditions. The simulated range reflects an uncertainty estimates that are obtained by varying the optimal parameters (A, C_p, β and a) one at a time within limits determined so that the minimum RMS error increases by 10 % or less. The results indicate that the wafer surface reaction temperature can be 2 to 12 degrees higher than the pad leading edge temperature at different polishing conditions.

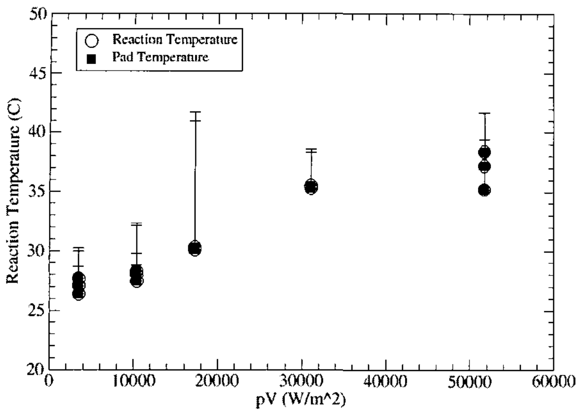

Fig. 5. Simulated reaction temperature ranges.

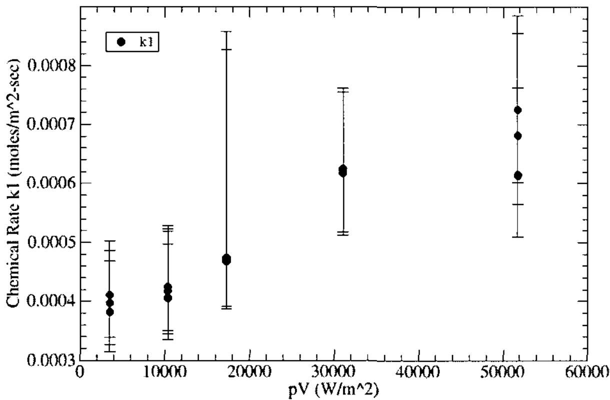

Fig. 6. Estimated ranges of the chemical rate constant k_1.

Figure 6 and 7 show the simulated range of the chemical rate constant k_1 and the mechanical rate constant k_2, respectively. The simulated range for the ratio of the chemical rate constant k_1 to the mechanical rate constant k_2 is shown in Fig. 8. The ratio (k_1/ k_2) indicates the chemical and mechanical action dominance during the polishing process. The simulated ratio ranges from 9 to 16 in the lowest $p\times V$ polishing condition, decreases gradually with the increase of the polishing power, and ranges from 1.6 to 3.3 at the highest $p\times V$ polishing condition. This shows that the polishing process is mechanical limited in the low $p\times V$ polishing region and becomes chemically and mechanically balanced with an increase of the polishing power.

5. CONCLUSION

In this study, a novel slurry containing ceria as the abrasive was analyzed in terms of its frictional, thermal and kinetic attributes for ILD CMP. The tribological

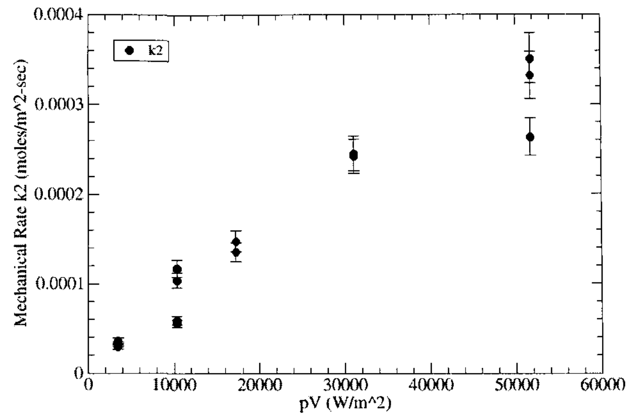

Fig. 7. Estimated ranges of the mechanical rate constant k_2.

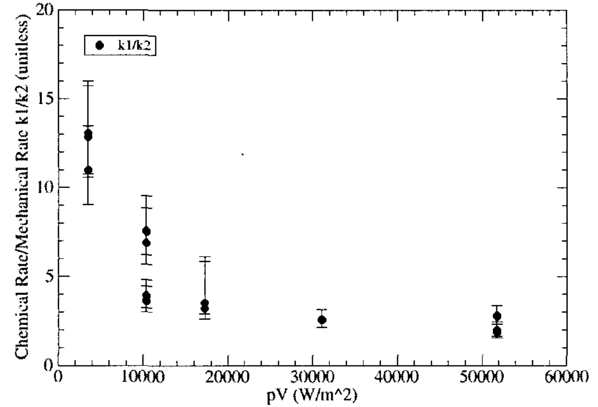

Fig. 8. Estimated ranges of the ratio of the chemical rate constant to the mechanical rate constant.

study indicates that boundary lubrication was the dominant lubrication mechanism during polishing. The ILD removal rate follows Prestonian (mechanical) behavior when $p\times V$ is less than 31,000 W/m^2 and shows evidence of chemically-influenced behavior at $p\times V$ =51,700 W/m^2. The ILD removal rate is variable at this polishing condition and shows a strong dependence on the average pad leading edge temperature. A modified two-step Langmuir-Hinshelwood kinetic model was used to simulate the ILD removal rate. The model uses transient flash heating to estimate the chemical reaction temperature and successfully simulates the non-Prestonian removal rate behavior at the $p\times V$=51,700 W/m^2. The model was used to analyze the chemical and mechanical action dominance and indicates that the polishing process was mechanical limited in the low $p\times V$ polishing region and became chemically and mechanically balanced with the increase of the polishing power.

REFERENCES

[1] Y. Zhuang, D. King, T. Kido, and A. Philipossian, "Frictional and removal rate studies of silicon dioxide and silicon nitride CMP using novel cerium dioxide abrasive slurries", Jpn. J. Appl. Phys., Vol. 44, No. 1A, p. 30, 2005.

[2] A. Philipossian and S. Olson, "Fundamental and removal rate studies of inter-layer dielectric chemical mechanical planarization", Jpn. J. Appl. Phys., Vol. 42, No. 10, p. 6371, 2003.

[3] J. Sorooshian, L. Borucki, D. Stein, R. Timon, D. Hetherington, and A. Philipossian, "Revisiting the removal rate model for oxide CMP", Trans. ASME J. Tribology, Vol. 127, No. 3, p. 639, 2005.