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Mathematical Modeling of Material Removal Rate in Roll-Type Linear CMP (Roll-CMP) Process: Effect of Polishing Pad

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Recently, a roll-type linear chemical mechanical polishing (Roll-CMP) process was developed for fabricating large flexible substrates such as flexible printed circuit boards (FPCBs). The major difference between the Roll-CMP and the conventional CMP is the type of contact between the polishing pad and the substrate. Roll-CMP uses line contact for material removal of the Cu film on FPCBs. Many researchers have studied mathematical models to understand the conventional CMP process. In this paper, a mathematical model on the material removal rate (MRR) of Roll-CMP is proposed based on Hertzian contact theory and previously studied models on conventional CMP to understand the effect of the polishing pad. Two kinds of polishing pads were prepared to investigate their effect on the material removal of copper clad laminate (CCL). The increase in the average radius of pad asperities over the standard deviation of pad asperities increases MRR. The slurry loading capacity of the polishing pad impacts the MRR of Cu as well. The proposed model may offer a theoretical understanding for the Roll-CMP process.

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NOMENCLATURE

a = half of contact width
L = length of roller
d = diameter of roller
E_p = elastic modulus of polishing pad
ν_p = Poisson's ratio of polishing pad
E_s = elastic modulus of substrate
ν_s = Poisson's ratio of substrate
F = down force
A = apparent area of contact
A_r = real area of contact
E_{ps} = composite elastic modulus of pad and substrate
R_p = average radius of pad asperities
σ_p = standard deviation of pad asperities
$F_m(b)$ = parabolic cylinder function
b = dimensionless separation (h/σ_p)
q = area density of particles in a slurry
N_a = number of active particles
χ = volume concentration of particles in a slurry
C_a = weight concentration of particles in a slurry
D_a = diameter of particle
ω_a = weight of single particle
ρ_s = density of slurry
ρ_a = density of particle
H_s = hardness of substrate
E_{ap} = composite elastic modulus of particle and pad
δ_p = indentation depth of particle into pad
δ_s = indentation depth of particle into substrate
$\zeta = 2\delta_p/D_a$
S = cross-sectional removal area
K = Rabinowicz's wear constant
MRR = material removal rate
V = relative velocity
A_s = total polished area of substrate
k = constant representing the effect of the slurry loading capacity of the polishing pad

1. Introduction

Chemical mechanical polishing (CMP) is one of the most widely used planarization processes for semiconductor fabrication due to its global planarization characteristics.[1-3] Application of the CMP process has expanded to other manufacturing fields such as printed circuit board (PCB) manufacturing. The fabrication processes of PCBs, especially flexible PCBs (FPCB), are now demanding a higher degree of integration and multi-stacking than before.[4] The CMP process is considered as one technique for metal-wiring in PCB fabrication to replace conventional etching. In previous research, a novel roll-type linear CMP (Roll-CMP) process that uses a line-contact material removal mechanism was developed for the fabrication of FPCBs to overcome tearing and folding issues in the polishing of flexible substrates.[5] The previous study showed that the material removal rate (MRR) of Roll-CMP has a linear relationship with the product of the applied pressure and the relative velocity. It is also experimentally revealed that the MRR relates to the polishing area in Roll-CMP.

Preston[6] reported the most important finding in the polishing process: the MRR is proportional to the pressure and relative velocity in the polishing process. However, the Preston constant in Preston's equation was an experimentally obtained value and included many effects from the process parameters. Many researchers have tried to define the Preston constant in detail with a mathematical approach based on contact mechanics.[7-9]

Qin et al.[10] studied the nonlinear behavior of the MRR in CMP. They proposed an equation for the real area of contact for a practical situation in the CMP process based on Johnson's contact mechanics.[11] Zhao and Chang[12] calculated the number of active particles that are embedded in the polishing pad on the real area of contact with the area density of slurry particles. Wang et al.[13] investigated a nonlinear contact model for single particle indentation on a soft polishing pad by using Sneddon's equation.[11] Jiang et al.[14] improved Zhao and Chang's model by considering the amorphous layer on the wafer surface in CMP. Chen et al.[15] considered the effects of particle deformation in CMP modeling. Lee et al.[16] established a semi-empirical MRR distribution model based on Qin's and Wang's model with a newly proposed calculation method for the number of active particles. Lee et al.[17] explained the effect of wafer size on the MRR of SiO_2 film with a mathematical model. However, a mathematical model for Roll-CMP has not been reported yet.

In the conventional CMP process, the polishing pad plays an important role in material removal. Generally, the MRR of CMP depends on many factors including macro- (groove) and microtexture (surface roughness) of the pad, and also the physical properties of the pad.[18] The polishing pads in CMP are classified into four types: polymer impregnated felts (Type I), poromerics (Type II), filled polymer sheets (Type III), and unfilled textured polymer sheets (Type IV).[19] Polishing pads for Roll-CMP require high flexibility and high slurry loading capacity so they can be coiled around the roller and transport the slurry to the pad-substrate interface. However, there has been little research conducted on polishing pads for Roll-CMP.

In this study, the effects of the polishing pad on the MRR are investigated for the Roll-CMP process with a mathematical model and experimental case study. Two felt-type polishing pads were prepared for Cu Roll-CMP experiments. The MRR characteristics are explained with a proposed mathematical model based on Hertzian contact theory, Qin's theory on the real area of contact, and Zhao's theory on the number of active particles and the indentation depth of each particle.

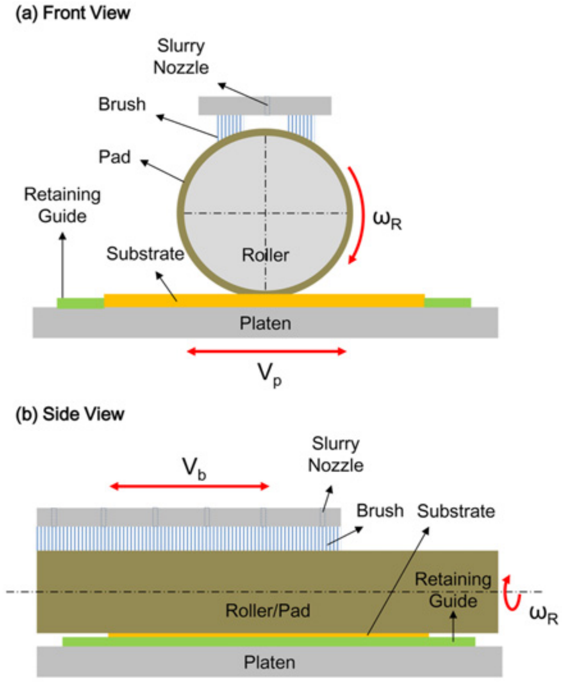

Fig. 1 Schematic of Roll-CMP system; (a) front view and (b) side view

2. Experimental Conditions

2.1 Roll-type linear CMP system

The Roll-CMP system consists of an oscillating platen, a roller, and oscillating slurry supply module including nozzles and brushes. The brush is used for both the in situ conditioning of the polishing pad and the uniform distribution of the CMP slurry. The sample (substrate) is located on the oscillating platen and it is fixed with the retaining guide to prevent the sample slippage. The polishing pad is tightly coiled around the roller. The roller is rotated clockwise with a DC servomotor while it is pressed against the substrate by a low-friction cylinder. The platen can be oscillated from side to side at a given speed. Two self-aligning bearings which are located at both ends of roller adjust horizontality. Fig. 1 is the schematic of the Roll-CMP system.

2.2 Consumables

Two felt-type of polishing pads (Pad 1 and Pad 2) were prepared for Roll-CMP experiments. The two polishing pads were made up of a felted fiber. As shown in Fig. 2, the polishing pads have a similar structure; however, the difference in them was the concentration of a polymer binder. As shown in Fig. 2, Pad 2 has a denser polymer binder than Pad 1. The compressibility of Pad 1 was 10% and that of Pad 2 was 4%. The thickness of both pads was 1.4 mm. All the prepared pads did not have an adhesive layer for ease of replacement.

A Cu CMP slurry was prepared for the polishing experiments. The

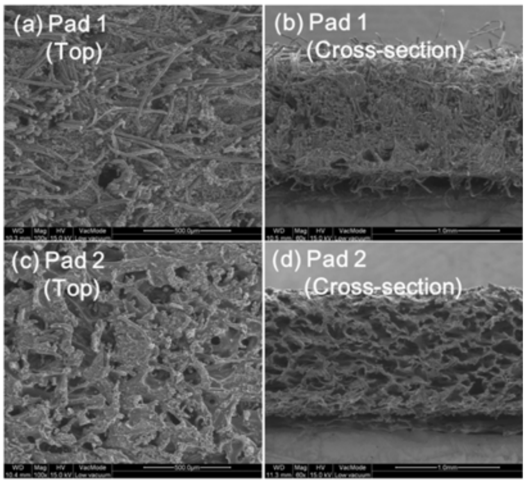

Fig. 2 Two types of polishing pads made of a felted fiber with a polymer binder (Adapted from Ref. 20 on the basis of OA)

Table 1 Information on CMP slurry

Type of particle	Colloidal silica
Particle size	70 nm
Particle concentration	3 wt%
Oxidizer	Hydrogen peroxide (H_2O_2)
Oxidizer concentration	1.7 wt%

concentration of oxidizer (hydrogen peroxide; H_2O_2) was 1.7 wt%. The concentration and size of colloidal silica was 3 wt% and 70 nm, respectively. The information on the CMP slurry is listed in Table 1.

2.3 Experimental setup

The down force was changed from 196.1 N to 343.2 N, and the relative velocity of the roller was varied from 72.87 m/min to 182.86 m/min. The oscillation length and speed of the platen were fixed to 110 mm and 7.5 mm/s, respectively. The slurry flow rate was 150 ml/min, and the polishing time was 5 min. The slurry temperature was 45°C. Copper clad laminates (CCLs) were used for the substrate, and its dimensions were 150 mm × 100 mm × 0.45 mm. The bulk copper layer was 20 ìm of thickness.

Before polishing, dummy polishing was performed for 30 min to stabilize the pad's condition. Between polishing steps, the polishing pad was cleaned with di-ionized water (DIW) and brushing.

The thickness change of the copper film was measured with a 4-point probe. The 30 points were measured with a 20 mm span along the x and y directions, respectively (6 points by 5 points).

3. Modeling

3.1 Apparent area of contact

The polishing pad which is tightly coiled around the roller contacts with the substrate by down force (F). The apparent area of contact (A) of the linear-type Roll-CMP system can be obtained from Hertzian contact theory.[21]

The half-width of contact (a) can be calculated as[21]

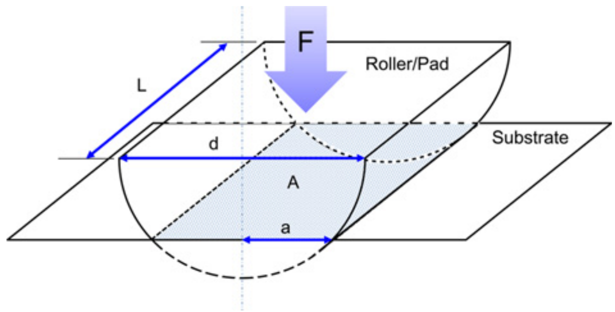

Fig. 3 Schematic of apparent area of contact in the Roll-CMP system

$$a = \left[\frac{2}{\pi L}\frac{(1-\nu_p^2)/E_p + (1-\nu_s^2)/E_s}{(1/d)}\right]^{1/2}\sqrt{F} \quad (1)$$

where L is the roller length; d is the roller diameter; ν_p is the Poisson's ratio of the polishing pad; ν_s is the Poisson's ratio of the substrate; E_p is the elastic modulus of the polishing pad; E_s is the elastic modulus of the substrate; and F is the applied down force.

The apparent area of contact between the pad and the substrate based on Hertzian contact theory can be written as

$$A = 2a \cdot L = \left[\frac{8L}{\pi}\frac{(1-\nu_p^2)/E_p + (1-\nu_s^2)/E_s}{(1/d)}\right]^{1/2}\sqrt{F} \quad (2)$$

The apparent contact area is determined from the material properties of the polishing pad, the substrate, and the applied down force. A previous study[5] showed that the contact area increased with the down force.

3.2 Real area of contact

The real area of contact is one of the most important factors in the polishing system. The polishing pad which is made up of a polymer-impregnated felt contacts with the substrate during polishing. The distribution of the pad asperity height follows the normal distribution. Qin et al.[10] proposed the real area of contact in CMP based on the Greenwood-Williamson (G&W) elastic contact model[22] and contact mechanics.[11] According to the G&W model, the contact between a plane and a nominally flat surface with asperities of radius R_p and a probability density function, the real area of contact can be expressed as[23]

$$A_r = \frac{3\pi}{4E_{ps}}\left(\frac{R_p}{\sigma_p}\right)^{1/2}\frac{F_1(b)}{F_{3/2}(b)}F = \left(\frac{1}{C}\right)\left(\frac{R_p}{\sigma_p}\right)^{1/2}\frac{pA}{E_{ps}} \quad (3)$$

where E_{ps} $(=((1-\nu_p^2)/E_p+(1-\nu_s^2)/E_s)^{-1})$ is the composite elastic modulus of pad and substrate; R_p is the average radius of pad asperities; σ_p is the standard deviation of pad asperities; F is the applied down force; p is the contact pressure; and A is the apparent area of contact.

For the case of peak-height distribution following a Gaussian height distribution, $F_m(b)$ is a parabolic cylinder function given by[23]

$$F_m(b) = \frac{1}{\sqrt{2\pi}}\int (s-b)^m e^{-s^2/2} ds \quad (4)$$

where b is the dimensionless separation (h/σ_p).

If we assume that the peak-height distribution follows a Gaussian height distribution, C $(=(4F_{1.5}(b))/(3\pi F_1(b)))$ can be drawn as shown in

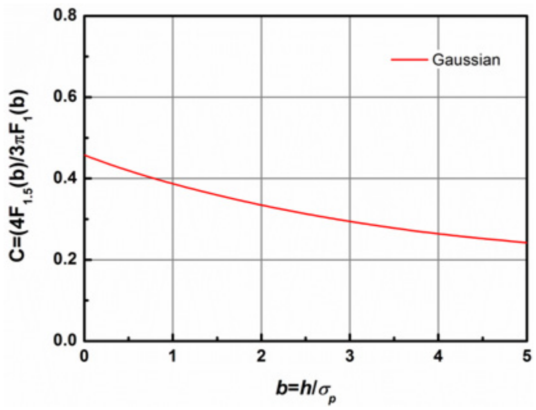

Fig. 4 C value as a function of the dimensionless separation (h/σ_p)

Fig. 4. Qin et al.[10] reported that the dimensionless separation b is 0.5-3.0. As b varies from 0.5 to 3.0, C is decreased from about 0.40 to 0.30. The average value of C (=0.35) is selected as a representative value for the convenience of calculation.

3.3 Number of active particles

Active particles in the polishing process are defined as the particles which participate in the material removal on the area of pad/substrate contact between two sliding surfaces. The number of active particles relates to the MRR in the polishing process. Zhao and Chang's assumptions[12] were adopted to calculate the number of active particles. The particles which are spherical with an average diameter D_a are uniformly distributed in the polishing slurry. The area density of the particles in the CMP slurry does not change during polishing.

The weight of a single particle ($\omega(D_a)$) can be calculated as[12]

$$\omega_a = \frac{1}{6}\pi D_a^3 \rho_a \tag{5}$$

where D_a is the diameter of a particle and ρ_a is its density.

The area density of the particles (q) is written as[12]

$$q = \left(\frac{6\chi}{\pi D_a^3}\right)^{2/3} \tag{6}$$

where χ is the volume concentration of the abrasive particles in the slurry.

The number of active particles which are participating in the wear process can be calculated by[12]

$$N_a = A_r\left(\frac{6\chi}{\pi D_a^3}\right)^{2/3} = A_r\left(\frac{6C_a\rho_s}{\pi D_a^3\rho_a}\right)^{2/3} \tag{7}$$

where A_r is the real area of contact; C_a is the weight concentration of particles in the slurry; and ρ_s is the density of the slurry.

Eq. (7) means that the number of active particles is the result of counting particles located on the real area of contact.

3.4 Indentation depth of particle

In the CMP process, the active particle located in the interface between the polishing pad and the substrate removes the chemically reacted layer using mechanical action. Assuming that the pad material is much softer than the substrate material, the particle indentation depth into the pad is larger than that into the substrate as shown in Fig. 5. According to Zhao and Chang's research,[12] plastic deformation occurs at the substrate-particle interface and the polishing pad is elastically deformed by particle indentation.

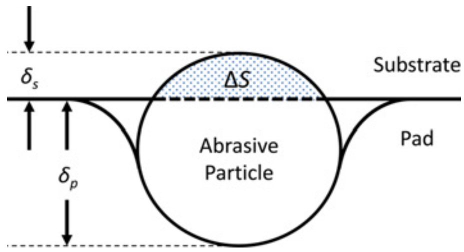

Fig. 5 Schematic of pad-particle-substrate contact

Wang et al.[13] proposed the indentation depth of a particle into the soft polishing pad and substrate by using force equilibrium in the pad-particle-substrate contact and parabolic approximation for the sphere profile. They also provided Eqs. (8)~(10) to solve for the dimensionless value ζ (Eq. (9)).[13]

$$\left(\frac{H_s}{E_{ap}}\right)^2 = \frac{1}{8\pi^2}\frac{\left(2\zeta+(\zeta-1)(-3+\sqrt{9+12\zeta})\right)^2}{(2-\zeta)^2(-3+\sqrt{9+12\zeta})} \tag{8}$$

$$\zeta = \frac{2\delta_p}{D_a} \tag{9}$$

$$\delta_s = \left(1-\frac{\zeta}{2}\right)D_a \tag{10}$$

where H_s is hardness of substrate, E_{ap} $(=((1-\nu_a^2)/E_a+(1-\nu_p^2)/E_p)^{-1})$ is the composite elastic modulus of a particle and pad, δ_p is the indentation depth of particle into pad; and δ_s is the indentation depth of a particle into the substrate.

3.5 Material removal rate model

In Fig. 5, the cross-sectional bow area left by the particle indentation on the surface of substrate is given by

$$\Delta S = \frac{4}{3}\delta_s\sqrt{\delta_s D_a} \tag{11}$$

The material removal volume per unit time (ΔG) is proportional to ΔSV with a constant K. V is the relative velocity, and K is Rabinowicz's wear constant which can be written as[24]

$$K = \frac{3}{\pi}\left(\frac{\delta_s}{D_a-\delta_s}\right)^{1/2} \tag{12}$$

The MRR can be expressed as

$$MRR = \frac{kK(\Delta S)VN_a}{A_s} = k\frac{5.6\delta_s^2}{A_s E_{ps} D_a^{3/2}\sqrt{D_a-\delta_s}}\left(\frac{R_p}{\sigma_p}\right)^{1/2}\left(C_a\frac{\rho_s}{\rho_a}\right)^{2/3} FV \tag{13}$$

where k is a constant that represents the effect of the polishing pad's slurry loading capacity and A_s is the total polished area of the substrate.

Eq. (13) means that the MRR in Roll-CMP relates to both the material properties of consumables (polishing pad, slurry, and substrate) and process conditions (down force and relative velocity).

Table 2 Material properties for mathematical modeling of Roll-CMP process

Parameter (Symbol)	Value	Unit
L	0.1	m
d	0.078	m
R_p	0.00005	m
σ_p	0.00003	m
E_s	1.1×10^{11}	Pa
ν_s	0.3	-
E_a	94×10^{9}	Pa
ν_a	0.2	-
E_p	900,000	Pa
ν_p	0.5	-
ρ_a	2270	kg/m^3
ρ_s	1040	kg/m^3
C_a	0.03	-
D_a	70	nm
A_s	0.011	m^2

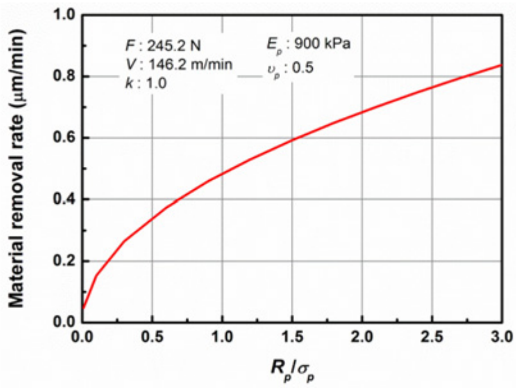

Fig. 6 Material removal rate as a function of roughness parameter (R_p/σ_p) in Roll-CMP

4. Results and Discussions

In the Roll-CMP process, the surface roughness of the polishing pad is kept constant with the brush of the oscillating slurry supply module. In Eq. (13), the parameter relating to the surface roughness of the polishing pad is R_p/σ_p which determines the real area of contact. Table 2 lists the material properties for mathematical modeling of the Roll-CMP process. Fig. 6 shows the MRR as a function of the roughness parameter (R_p/σ_p). The elastic modulus and Poisson's ratio were assumed at 900 kPa and 0.5, respectively. The down force was 245.2 N, and the relative velocity was 146.2 m/min. The k value was 1. According to Eq. (13), the MRR increases with R_p/σ_p. The increase in average radius of pad asperities and the decrease in standard deviation of pad asperities lead to the increase in the number of active particles.

The major differences between Roll-CMP and conventional CMP are the type of pad-substrate contact and the slurry supplying method. In Roll-CMP, the polishing pad coiled around the roller makes a line contact with a substrate. The CMP slurry is supplied on the top of the spinning polishing pad. These systematical differences might relate to the MRR with slurry participation capacities of the polishing pad.

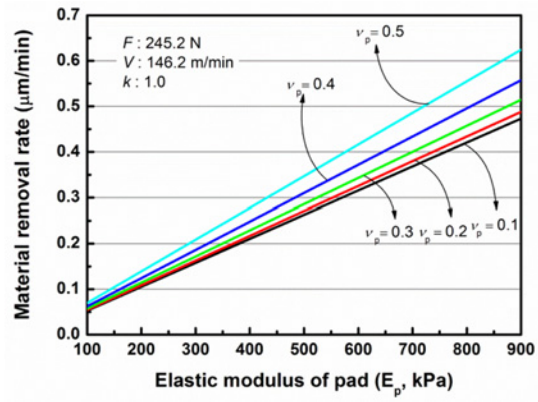

Fig. 7 Effect of elastic modulus and Poisson's ratio of the polishing pads based on the proposed model

Table 3 Material properties of two polishing pads

Parameter (Symbol)	Value	Unit
E_p (Pad 1)	0.620×10^{6}	Pa
ν_p (Pad 1)	0.5	-
E_p (Pad 2)	0.880×10^{6}	Pa
ν_p (Pad 2)	0.5	-

Assuming that the elastic modulus and Poisson's ratio of the polishing pads are controlled by the type of materials, and they have same microtexture, the constant k, which represents the effect of the slurry loading capacity of the polishing pad, might be the same. In this case, the MRR increases with the elastic modulus and Poisson's ratio of a polishing pad as shown in Fig. 7. However, material properties of the normal felt-type polishing pads change with the density of the polymer binder. This might cause a difference of k values in the felt-type polishing pads.

In this paper, two types of polishing pads were prepared to verify the proposed model and to find the k values experimentally.

As shown in Fig. 2, the two polishing pads differ in their microtexture. Pad 2 contains more polymer binder than Pad 1. The difference in the microtexture relates to the mechanical properties of the polishing pad. Table 3 lists the material properties of two polishing pads.

Fig. 8 shows the experimental MRRs and modeling results as a function of FV. The experimental results show that the MRR is linearly increased with FV according to Preston's model. When we set k=1 in Eq. (13), Pad 2, which has a higher elastic modulus, shows higher MRR than Pad 1. On the other hand, the experimental results show that Pad 1 has higher MRR than Pad 2. The conflicting results between experimental results and modeling results come from the constant k, which represents the effect of the slurry loading capacity of the polishing pad. In Cu CMP, chemical reactions have a greater effect in comparison with oxide CMP. The general mechanism of the Cu CMP usually consists of chemical dissolution, mechanical abrasion, and the synergistic cooperation of these two mechanisms.[25] Thus, the slurry loading capacity largely impacts the material removal of the copper film. The slurry loading capacity depends on the microtexture of the pad and also relates to the compressibility in various felt-type polishing pads. From the experimental results and Eq. (13), the k values for Pad

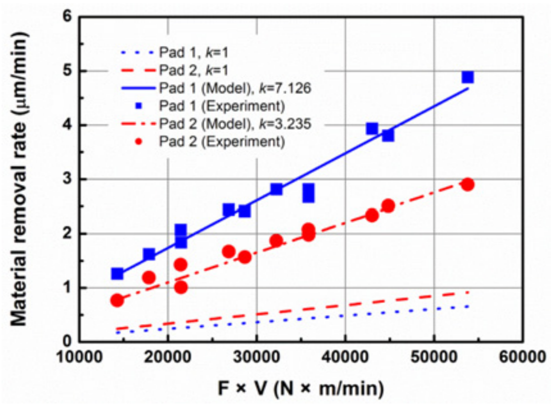

Fig. 8 Experimentally obtained material removal rates and modeling results as a function of *FV*

1 and Pad 2 are determined as 7.126 and 3.235, respectively. The *k* value of Pad 1 is 2.2 times higher than that of Pad 2. Considering the compressibility of Pad 1 is 2.5 times higher than that of Pad 2, the *k* value may relate to the compressibility of the polishing pad because the polishing pad squeezes the absorbed CMP slurry at the pad-substrate contact area in Roll-CMP. Thus, the *k* values in Fig. 8 indicate the slurry loading capacity of polishing pads under the same process conditions. The results show that the slurry loading capacity of Pad 1 is 2.2 times higher than that of Pad 2.

5. Conclusions

In this paper, a mathematical model for roll-type linear CMP was proposed to investigate the effects of polishing pads on the MRR of Cu. Two felt-type polishing pads were prepared to understand the material removal characteristics.

In the Roll-CMP, a line-contact material removal mechanism was used for material removal. The proposed model indicates that the increase in the average radius of pad asperities and the decrease in standard deviation of pad asperities increase MRR under constant material properties of the polishing pad. MRR was determined with the slurry loading capacity of the polishing pad as well because Roll-CMP differs from the conventional CMP process in the type of pad-substrate contact and the slurry supplying method. The proposed model may help a theoretical understanding of the Roll-CMP process.

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REFERENCES

1. Lee, H., Park, Y., Lee, S., and Jeong, H., "Preliminary Study on the Effect of Spray Slurry Nozzle in CMP for Environmental Sustainability," Int. J. Precis. Eng. Manuf., Vol. 15, No. 6, pp. 995-1000, 2014.
2. Lee, H., Guo, Y., and Jeong, H., "Temperature Distribution in Polishing Pad during CMP Process: Effect of Retaining Ring," Int. J. Precis. Eng. Manuf., Vol. 13, No. 1, pp. 25-31, 2012.
3. Lee, H., Dornfeld, D. A., and Jeong, H., "Mathematical Model-based Evaluation Methodology for Environmental Burden of Chemical Mechanical Planarization Process," Int. J. Precis. Eng. Manuf. -Green Tech., Vol. 1, No. 1, pp. 11-15, 2014.
4. Wang, H., Lee, H., and Jeong, H., "Statistical Analysis on Process Variables in Linear Roll-CMP," Journal of the Korean Society of Tribologists and Lubrication Engineers, Vol. 30, No. 3, pp. 139-145, 2014.
5. Lee, H., Wang, H., Park, J., and Jeong, H., "Experimental Investigation of Process Parameters for Roll-Type Linear Chemical Mechanical Polishing (Roll-CMP) System," Precision Engineering, Vol. 38, No. 4, pp. 928-934, 2014.
6. Preston, F., "The Theory and Design of Plate Glass Polishing Machines," Journal of the Soc Glass Technology, Vol. 11, pp. 214-256, 1927.
7. Tseng, W. T., Chin, J. H., and Kang, L. C., "A Comparative Study on the Roles of Velocity in the Material Removal Rate during Chemical Mechanical Polishing," Journal of the Electrochemical Society, Vol. 146, No. 5, pp. 1952-1959, 1999.
8. Guo, L. and Subramanian, R. S., "Mechanical Removal in CMP of Copper using Alumina Abrasives," Journal of The Electrochemical Society, Vol. 151, No. 2, pp. G104-G108, 2004.
9. Homma, Y., "Dynamical Mechanism of Chemical Mechanical Polishing Analyzed to Correct Preston's Empirical Model," Journal of the Electrochemical Society, Vol. 153, No. 6, pp. G587-G590, 2006.
10. Qin, K., Moudgil, B., and Park, C.-W., "A Chemical Mechanical Polishing Model Incorporating both the Chemical and Mechanical Effects," Thin Solid Films, Vol. 446, No. 2, pp. 277-286, 2004.
11. Johnson, K. L., "Contact Mechanics," Cambridge University, p. 406, 1985.
12. Zhao, Y. and Chang, L., "A Micro-Contact and Wear Model for Chemical-Mechanical Polishing of Silicon Wafers," Wear, Vol. 252, No. 3, pp. 220-226, 2002.
13. Wang, Y., Zhao, Y.-W., and Gu, J., "A New Nonlinear-Micro-Contact Model for Single Particle in the Chemical-Mechanical Polishing with Soft Pad," Journal of Materials Processing Technology, Vol. 183, No. 2, pp. 374-379, 2007.
14. Jiang, J.-Z., Zhao, Y.-W., Wang, Y.-G., and Luo, J.-B., "A Chemical Mechanical Polishing Model based on the Viscous Flow of the Amorphous Layer," Wear, Vol. 265, No. 7, pp. 992-998, 2008.
15. Chen, X., Zhao, Y., and Wang, Y., "Modeling the Effects of Particle Deformation in Chemical Mechanical Polishing," Applied Surface

Science, Vol. 258, No. 22, pp. 8469-8474, 2012.

16. Lee, H. S., Jeong, H. D., and Dornfeld, D. A., "Semi-Empirical Material Removal Rate Distribution Model for SiO_2 Chemical Mechanical Polishing (CMP) Processes," Precision Engineering, Vol. 37, No. 2, pp. 483-490, 2013.

17. Lee, H., Park, Y., Lee, S., and Jeong, H., "Effect of Wafer Size on Material Removal Rate and Its Distribution in Chemical Mechanical Polishing of Silicon Dioxide Film," Journal of Mechanical Science and Technology, Vol. 27, No. 10, pp. 2911-2916, 2013.

18. Park, K. H., Kim, H. J., Chang, O. M., and Jeong, H. D., "Effects of Pad Properties on Material Removal in Chemical Mechanical Polishing," Journal of Materials Processing Technology, Vol. 187, No. pp. 73-76, 2007.

19. Oliver, M. R., "Chemical-Mechanical Planarization of Semiconductor Materials," Springer, p. 172, 2004.

20. Wang, H., "Effect of Pad Viscoelastic Behavior on Polishing Characteristics in Roll-CMP Process," M.Sc. Thesis, Department of Mechanical Engineering, Pusan National University, 2015.

21. Budynas, R. G. and Nisbett, K. J., "Shigley's Mechanical Engineering Design," McGraw-Hill, p. 124, 2011.

22. Greenwood, J. A. and Williamson, J. B. P., "Contact of Nominally Flat Surfaces," Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, Vol. 95, pp. 300-319, 1966.

23. Bhushan, B., "Principles and Applications of Tribology," John Wiley & Sons, 2nd Ed., pp. 234-236, 2013.

24. Rabinowicz, E., "Friction and Wear of Materials," 2nd Ed., Wiley, 1995.

25. Xu, G., Liang, H., Zhao, J., and Li, Y., "Investigation of Copper Removal Mechanisms during CMP," Journal of The Electrochemical Society, Vol. 151, No. 10, pp. G688-G692, 2004.