# Tribological Issues and Modeling of Removal Rate of Low-*k* Films in CMP

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Mechanical and tribological properties of various doped and undoped oxide low-*k* materials like undoped  $(SiO_2)$ , carbon-doped (SiOC), and fluorine-doped (SiOF) oxides are investigated by studying the removal rates at different pressure and velocity conditions. In addition to verifying the Preston equation, a comprehensive physics and statistics based model called the abrasion model is modified and validated based on experimental data. The model is derived on the basis that the material removal rate (MRR) is equal to the material removed by a single abrasive and the number of active abrasives involved in material removal. Apart from the primary factors like pressure and velocity, details like pad hardness, pad roughness, abrasive size, and abrasive size distributions are also included in the model. It is found that with the increase in pressure, MRR increases due to increase in the research specimens has been carried out on a prototype of an actual CMP machine called the Universal Bench Top CMP tester. © 2004 The Electrochemical Society. [DOI: 10.1149/1.1643746] All rights reserved.

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In the semiconductor industry chemical mechanical planarization (CMP), developed at IBM during the early 1980s, has emerged as the fastest growing operation and is expected to show equally explosive growth in the future.<sup>1,2</sup> The process was mainly used to polish dielectrics and more recently for polishing interconnect metals in multilayer chips.<sup>3</sup> The CMP process is a tribochemical process which involves a simultaneous interaction between polishing slurry, a semiconductor wafer, and a polyurethane pad. The chemical, mechanical, and material properties of the pad, wafer surface, and slurry determine the controllability and quality of CMP. The last ten years have witnessed significant advancements in both the development of more sophisticated processing tools and newer process consumables.<sup>4</sup> An ideal CMP process is expected to produce excellent global planarity, good surface finish, high removal rates, low surface defectivity, and high selectivity with regard to the underlying layers (particularly in metal polishing and in shallow trench isolation), all without the introduction of surface topography such as dishing and erosion.<sup>3</sup> A detailed study of the interaction between the wafer surface, pad, and slurry particles is necessary to produce the results of an ideal CMP process. Most analyses focus on studying the mechanical and chemical effects on the process separately. In this paper, though, there is more emphasis on the mechanical effect. Its correlation with the chemical effect is also discussed with the help of a comprehensive physics and statistics based model called the abrasion model. An attempt has been made to explain the complex interactions between the wafer-abrasives and wafer-pad interfaces with the help of the abrasion model.

The mechanical interaction between wafer, pad, and slurry has been the subject of research for some time.<sup>5-10</sup> The most basic and referred to model to describe the CMP process was first given by Preston (1927),<sup>9</sup> stating that the material removal rate (*MRR*) = KpPV. According to Preston's equation the removal rate is directly proportional to the pressure (*P*) applied and the relative velocity (*V*) of the pad. *Kp* is the Preston coefficient. In his equation the pressure applied P = L/A, where *L* is the load applied and *A* is the area contacting the pad. This area of contact need not necessarily be the geometric area of the surface or the actual area of surface, because wafer surfaces (mostly patterned) have severe topography or a rough surface. In such a case, it cannot be assumed that the area on which the load acts is the geometric area of the surface being polished. Because of this many researchers opined that Preston's equation holds good only when there is a smooth surface. Preston's equation has proved to be reasonably accurate for SiO<sub>2</sub>, Cu, and W (tungsten) CMP, but the dependence of *Kp* on process variables like slurry composition and pad properties was not well understood.

Experimental results show that slurries composed of abrasives and pad materials have larger influence on material removal rate than just the platen speed and down pressure.<sup>11-14</sup> Several models that predict and explain the material removal mechanisms in CMP have been reported,<sup>10-16</sup> most of which are based on the mechanical aspects of CMP. Some of the important aspects in addition to pressure and velocity are properties of consumables like the pad and slurry. Minute details of the pad, such as the asperity distribution, asperity height, and asperity radius, have also shown to affect the rate of material removal.<sup>17</sup> Oliver et al.<sup>18</sup> proposed an asperity contact model for CMP. Their results indicate that the polish rate is a sensitive function of the asperity height distribution. A modification to Preston's equation to reaccount for the dependencies of removal rate on pressure and rotational speed during the CMP process was made by Tseng and Wang.<sup>19</sup> They proposed  $MRR = MP^{5/6}V^{1/2}$ , where M is the weighting factor to removal rate from other processes like slurry attack. Zhao and Shi<sup>20</sup> proposed another model that was contrary to Preston's model. Their experiments were carried out using a soft polishing pad. They proved with experimental results that pressure dependence of the removal rate for CMP with soft pads is nonlinear. They also stated that there is a difference between polishing with a hard pad and a soft pad. Their model states that  $MRR = K_{sz}P^{2/3}V$ , where  $K_{sz}$  is a function of other CMP variables. In the case of soft pads, pad hardness is much less than the hardness of the abrasives and the wafer surface. Certain important factors are not considered in this model; for example, if the contact area increases there is a decrease in the force applied on the abrasives, which leads to smaller amounts of material removed by each. Zhao and Shi<sup>21</sup> recognized this limitation of the model and introduced a threshold pressure  $P_{\rm th}$ , arguing that only when the down pressure is larger than the threshold pressure will material removal occur. They revised the earlier equation and proposed an equation to include the threshold pressure, which is given by MRR =  $KV(P^{2/3} - P_{th}^{2/3})$ ; what is exactly included in the all-purpose coefficient K is still unclear.<sup>22</sup> Most of the models mentioned do not take all possible scenarios into consideration. Some of them studied the behavior of pressure and velocity in contrast to Preston's equa-tion. For example, Zhang *et al.*<sup>23,24</sup> proposed an equation MRR=  $K_{\rm p}(PV)^{1/2}$ , taking into account the normal stress and shear stress acting on the contact area between abrasive particles and wafer surfaces

However, most models were quite inadequate. Few researchers have considered only the pad effects while few others have consid-

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ered only the effects of slurry flow. As the knowledge of CMP process and the role of consumables improved over the years, the material removal rate models also improved. Ahmadi and Xia<sup>16</sup> proposed a model for mechanical wear in CMP processes by taking into account different possible cases. Basically, mechanical contact theory was used to develop a model for pad asperities with abrasive particles in slurry and wafer. Different cases of pads (hard and soft) and slurries (dilute and dense) were analyzed. In their work the material removal rate variation with pressure, abrasive size, and concentration as well as pad characteristics (asperity distribution, pad elastic, and plastic deformation) were studied. According to Ahmadi and Xia<sup>16</sup> the wear in CMP occurred in four different ways: abrasive wear, adhesive wear, corrosive wear, and erosive wear. They believed that in CMP, abrasive and adhesive wear are the main wear mechanisms. Their removal rate model stated that MRR =  $sRR_{abrasive} + (1 + s)RR_{adhesive}$ , where s is the probability that the abrasive particles will roll against the wafer during CMP. Their paper includes polish rate models for different cases like removal by abrasive wear and removal by adhesive wear, each of these cases having subcases like abrasive wear with hard pad and dense slurry, abrasive wear with hard pad and dilute slurry, adhesive wear with soft pad and dense slurry, and adhesive wear with hard pad and dense slurry with plastic deformation, etc. But even here the chemical effects on CMP were not considered.

Apart from models that predict removal rate, a few models that control the CMP process by a run-by-run controller design were also proposed in literature.<sup>25</sup> Many models, some based on fluid dynamics, some on contact mechanics, some physics-based models, chemistry-based models, statistics-based models, and some mathematical models were proposed by several researchers.<sup>26-32</sup> Most of the models worked on improving Preston's equation, as Preston's equation could not express exactly the effect of consumable properties on the removal rate and could not be used for accurate removal rate prediction. A model proposed recently by Luo and Dornfeld<sup>22</sup> is the subject of investigation in this paper. This model was chosen in comparison to most other models existing in literature because it not only includes macroscale details of the process but also microscales details associated with the consumables used. Their model is focused on studying the material removal occurring due to contact between the abrasive-pad and abrasive-wafer interfaces. Their model integrates process parameters including pressure and velocity in addition to other important input variables like pad and wafer hardness, pad roughness, abrasive size, abrasive size distribution, and abrasive geometry and is given by the basic expression

$$MMR_{\rm mass} = \rho_{\rm w} NVol_{\rm removed} + C_0$$
[1]

where the mass of material removed (*MRR*<sub>mass</sub>) is equal to the amount of material removed (*Vol*<sub>removed</sub>) by a single particle of the slurry in unit times the number of particles actively involved in material removal (*N*).  $\rho_w$  is the density of the wafer material and  $C_o$  is the material removed due to chemical etching. This equation gives a skeleton representation of the model. A detailed expression and explanation of the model with the assumptions and derivations are given in the following sections of the paper.

From this discussion it is seen that the CMP process is a complex process because of the various factors that should be considered in order to characterize the process and achieve a globally usable model. Luo and Dornfeld proposed one such model in 2001.<sup>22</sup> In this paper, their model has been further investigated and an attempt has been made to modify the model when different doped and undoped oxides were subjected to CMP. The model is also experimentally validated by substituting the experimental conditions into Luo and Dornfeld's model and then comparing the removal rate obtained by running the experiments at those conditions with the removal rate obtained by using Luo and Dornfeld's model, which predicts the *MRR* for a given set of conditions. The main purpose of this study is to apply the implications of the model to understand the tribological properties of different low-*k* films, which will allow optimization of

Table	I.	Details	of	testing	paramet	ters and	l consum	ables	s used	for
CMP	exp	perimen	ıts.							

Normal pressure	Variable (1-6 psi)
Platen rotation	Variable (0.2-1.2 m/s or 42.2-254.6 rpm)
Slider movement	45 mm with offset $\pm 5$ mm and velocity 10 mm/s
Slurry	Oxide slurry (Klebesol 1501), (75 mL/min)
Pad	IC1000-B4/SubaIV
Time	20-80 s
Upper specimen	Undoped and doped silicon oxide

pad design, material selection, down force, and orbital and linear speed. Another central motivation behind this work is to test the applicability of a bench-top CMP tester (CETR Inc., CA) as a real-time R&D tool. If the predicted and experimental values match, it can be concluded that the bench-top tester can be used for real-time R&D. The assumptions, experiments, and results are discussed in this paper.

## Experimental

All the materials studied in this work were polished on a benchtop CMP tribometer provided by CETR, Inc., CA. It is essentially a bench-top CMP machine with a number of signals monitored and analyzed *in situ*. The polishing of the samples to be tested was performed with a variety of process parameters after optimal settings of the machine were decided based on extensive experimentation. Details of the tester and its optimization have been discussed earlier.<sup>33</sup>

In this paper only the type of method used to grow the films over a silicon substrate are mentioned. Wolf and Tauber<sup>34</sup> give detailed explanations of the fabrication processes of the samples used in the study. Undoped silicon dioxide (SiO<sub>2</sub> U) was deposited on a Si wafer using plasma-enhanced chemical vapor deposition (PECVD) in a six-station sequential deposition system. The gases used were SiH<sub>4</sub>, N<sub>2</sub>O, and N<sub>2</sub>. The deposition temperature was 400°C. A Carbon-doped oxide film grown with standard precursors (SiOC SP) is a carbon-doped silicon dioxide, also known as carbon-doped siloxane or organosilicate glass (OSG). The precursor used is a liquid and is called tetramethylcyclotetrasiloxane (TMCTS). The low-k carbon-doped film is deposited using PECVD at 400°C in a six-station sequential deposition system.<sup>35</sup> SiOC NSP (SiOC grown with nonstandard precursors) dielectric film was deposited using tetramethylsilane gas using PECVD at 400°C in a six-station sequential deposition system. SiOC SO (SiOC grown by spin-on method), a siloxane polymer-based material, is an organic and inorganic hybrid. It is a spin-on dielectric and has flowable characteristics. SiOF is a fluorine-doped silicon dioxide film. It is deposited using inductively coupled high-density plasma chemical vapor deposition (HDP-CVD) with SiF<sub>4</sub>, SiH<sub>4</sub>, O<sub>2</sub>, and Ar at 400°C.<sup>36</sup> These samples were polished at the conditions reported in Table I. Nine samples of each kind at different pressure and velocity conditions were polished, with no conditioning in between. Break-in was done at the beginning of the experiment for 20 min with deionized water with a diamond conditioner.

Details of the samples along with mechanical properties measured using a nanoindentation technique<sup>37</sup> are given in Table II. Table I describes the testing parameters and materials for measuring wear behavior of oxides. These process settings were chosen after running a series of dummy samples and the wear rate was examined by optical inspection.

For removal rate calculations (experimental), thickness of the oxide layer was measured using an ellipsometer. The measurements were taken at nine points on the wafer before and after polishing. The thickness was calculated by subtracting the final average thickness from the initial average thickness. The material removal rate was calculated as  $MRR = thickness_{initial} - thickness_{final}/time$ . This is compared with the theoretical results.

Table II. Detai	ls of the samples and in	dentation results of the oxide-base	ed, low-k samples.		
Sample	Thickness (Å)	Growth method	Hardness (GPa)	Modulus (GPa)	Refractive index
SiO <sub>2</sub> U	3850	PECVD	6.3 ± 1.2	$68.1 \pm 1.2$	1.474
SiOF	1700	HDPCVD	$4.3 \pm 0.70$	$42.4 \pm 3.4$	1.430
PE					
SiOC	4350	PECVD and Std.	$1.3 \pm 0.17$	$8.8 \pm 0.3$	1.390
SP		precursor			
SiOC	3550	PECVD and nonstd.	$1.7 \pm 0.50$	$6.1 \pm 1.26$	1.415
NSP		precursor			
SiOC	6600	Spin-on	$0.3 \pm 0.04$	$4.5 \pm 0.5$	1.370
SO					

## **Theoretical Aspects**

In this paper a model proposed by Luo and Dornfeld<sup>22</sup> is chosen as a reference model to be validated using experimental data obtained during polishing doped and undoped blanket oxides on a CMP tester. A new method of calculating the number of active abrasives has been proposed and included in the model. Due to the increasingly strict process requirements in manufacturing future generation integrated circuit (IC) chips, a detailed model, which takes even minute details into consideration and is accurate, is needed for a better understanding of the CMP process. Verification of the most referred Preston's equation provides useful insight into the influence of pressure and velocity on the rate of material removed, but any discrepancies that may follow are usually attributed to the all-purpose parameter  $K_p$ . Luo and Dornfeld's model investigated microscale details like the abrasion mechanism caused by the nanoscale abrasives, small pad hardness, and different size scales of pad asperity and polishing abrasives.<sup>22</sup> The proposed model called the abrasion model assumes a solid-solid contact mode and twobody abrasion action as shown in Fig. 1.

The model is derived mainly by calculating the amount of material removed by a single abrasive particle of the slurry and determining the number of particles involved in the removal of material. One of the assumptions was that the polishing pad has periodic roughness, which helped in analyzing the actual contact area between the polishing pad and the wafer surface and in understanding the role played by the density of the asperities.<sup>22</sup> The model assumed plastic deformation between the interfaces of wafer and abrasive and the abrasive and pad. This assumption helped in calculating the volume removed by a single abrasive particle, by calculating the deformation between the wafer-abrasive and pad-abrasive interfaces, and is given by the equation

$$Vol_{\rm removed} = \frac{\sqrt{2}}{3} \frac{x_{\rm avg-a}^2}{(b_1 H_{\rm w})^{3/2}} \sqrt{P_0} V$$
 [2]

where  $x_{avg-a}$  is the average active abrasive particle size,  $b_1$  is a constant and is equal to  $\pi (3R/4)^{2/3} D_{sum}^{1/3}$ , *R* is the radius of the asperities, and  $D_{sum}$  is the density of the asperities per unit area.  $H_w$  is the hardness of the wafer and  $P_0$  and *V* are the down pressure and platen speed, respectively. The model suggests that the material re-



Figure 1. Schematic representation of two- and three-body abrasions in CMP process.

moved is equal to the volume of material removed by a single abrasive multiplied by the number of abrasives actively involved in material removal. Luo and Dornfeld's model was developed for large pressure and small velocity conditions. In order to test the validity of this model a wide range of conditions, including both high and low velocity and pressure ranges, are considered. In order to calculate the number of active abrasives involved in the material removal, normal distribution of the size of abrasive particles was assumed. The number of active abrasives was given as

$$N \approx \frac{\rho_{s}m_{s-a}A_{a}}{\rho_{a}\frac{\pi}{6}x_{avg}^{3}}D_{sum}al\left[1-\Phi\left(3\right) - \frac{0.25 \times \left(\frac{4}{3}\right)^{2/3}(x_{avg}+3\sigma)\left(\frac{1}{H_{p}}+\frac{2}{H_{w}}\right)}{\sigma}\frac{E_{p}^{2/3}}{b_{1}}P_{0}^{1/3}\right]$$
[3]

where *N* is the number of active abrasives,  $\rho_s$  is the density of the slurry before dilution,  $m_{s-a}$  is the concentration of slurry before dilution, and  $\rho_a$  is the density of the abrasive.  $A_a$  is the apparent contact area,  $x_{avg}$  is the average size of the abrasive, *a* is the mean area of a single asperity, *l* is the height of the asperities,  $\sigma$  is the standard deviation of the abrasive size,  $H_p$  is the hardness of the pad,  $P_0$  is the pressure applied, and  $E_p$  is the Young's modulus of the pad. Detailed explanations of the model derivation are given in Ref. 22. Substituting Eq. 2 and 3 in Eq. 1, we get



Figure 2. Schematic representation of the influence of down pressure on the number of active abrasives trapped at the wafer-pad interface.

Table III. Change in the number of abrasives trapped between pad and wafer during polishing at different polishing conditions. These numbers vary with a variation in the down pressure and actual area of the samples.

Valoaity	Pressure (psi)	Number of abrasives trapped between the pad-wafer interface $(n)$					
(m/s)		SiO <sub>2</sub> U	SiOF	SiOC SP	SiOC NSP	SiOC SO	
0.2	1	263450119.6	261045624.3	265883259.9	254062544.3	248889565	
0.8	1	255167969.3	260551869.2	235996368.2	260501770.5	248448238.7	
1.2	1	261341435.5	266477212.4	245931654.2	271851550.6	235807945.7	
0.2	3	478390421.2	507306475.4	507721486.9	524409929.4	478409544.7	
0.8	3	533493578.1	520984417.5	491705820.9	515497990.1	491896653.9	
1.2	3	515350064.4	519414846.6	514462671.1	518262135.2	460862394.1	
0.2	6	763342754.7	780116971.6	780997173.6	820234920.4	723689916.1	
0.8	6	799488887.1	818581784.7	792669039.5	751871203.2	680301612.8	
1.2	6	745115716.5	777393202.8	725350162.9	749238793.1	701885302.3	

$$MRR_{\text{mass}} = \frac{3\sqrt{2}}{2} k^2 \rho_{\text{w}} A_{\text{a}} \frac{\rho_{\text{s}} m_{\text{s}-\text{a}} D_{\text{sum}} a l}{\rho_{\text{a}} \pi x_{\text{avg}}} \frac{1}{(bH_{\text{w}})^{3/2}} \left[ 1 - \Phi \left( 3 - \frac{0.25(x_{\text{avg}} + 3\sigma) \left( \frac{1}{H_{\text{p}}} + \frac{2}{H_{\text{w}}} \right)}{\sigma} \frac{P_0}{b} \right) \right] P_0^{3/2} V [4]$$

In this equation  $k = 1 + (3\sigma/x_{avg})$  and *b* is the ratio of apparent contact area  $A_a$  and real contact area *A*. The thickness removed per unit time is often used to approximate the removal rate. It is given by

$$MRR_{\rm thickness} = \frac{MRR_{\rm mass}}{\rho_{\rm w}A_{\rm a}}$$
[5]

In addition to the assumptions made by Luo and Dornfeld, another assumption with regard to the influence of pressure on the number of particles involved in material removal is made in this work. Luo and Dornfeld stated that the number of abrasives captured over the wafer-pad contact area is independent of the pressure in their model, but we assume that the number of abrasives in the wafer pad interface would increase with an increase in pressure. A schematic of the pad-wafer interface and the influence of pressure on the active number of abrasives trapped are shown in Fig. 2. The actual method of calculations is explained in the coming sections. Also, if we take a look at the term  $1/(bH_w)^{3/2}$  in Eq. 4 it is seen that the hardness of the wafer  $(H_w)$  does not have a large influence on the *MRR* as

$$b = \frac{P_0}{P} = \frac{0.5P_0 x_{\text{avg}-a}}{R_a H_w}$$
[6]

(from Ref. 22). Also from Table III it is clear that  $H_p \ll H_w$ . Therefore, considering the assumption that the wafer hardness is much higher than that of the pad, we can say that  $1/H_p + 2/H_w$  $\approx 1/H_p$ . We have tried to calculate  $MRR_{mass}$  using the calculated or estimated values of the constants in the equation, instead of trying

Table IV. Variation of contact area ratio b (ratio of apparent contact area  $A_a$  and real contact area A) for different samples with different hardness at different down pressure.

	Contact area ratio, b			
Sample	1 psi	2 psi	3 psi	
SiO <sub>2</sub> U	0.00083921	0.002518	0.005035	
SiOF	0.0011212	0.003364	0.006727	
SiOC SP	0.00379071	0.011372	0.022744	
SiOC NSP	0.00284303	0.008529	0.017058	
SiOC SO	0.0146641	0.043992	0.087984	

to find out the unknown values using experimental values of  $MRR_{\rm mass}$ . In the process we observed that the dependency of  $MRR_{\rm mass}$  on  $H_{\rm w}$  appears to be only due to the term *b* occurring in the expression

$$\left[1 - \Phi\left(3 - \frac{0.25(x_{avg} + 3\sigma)\left(\frac{1}{H_p} + \frac{2}{H_w}\right)}{\sigma} \frac{P_0}{b}\right)\right]P_0^{3/2}V$$

Here it was observed that  $MRR_{mass}$  was directly proportional to the hardness of the material, while it should have been otherwise. Hence, we see that in our calculations  $MRR_{mass}$  for harder materials is more than that of the softer materials. Further work in this direction needs to be done so that the dependence of  $MRR_{mass}$  on  $H_w$  is made more clear. Also, when we substitute the value of *b* in Eq. 4 we see that the *MRR* is greatly dependent on the roughness ( $R_a$ ) of the polished wafers. Another proposition to include the complete effect of  $H_w$  on *MRR* is the consideration of the hardness of the film at the wafer-slurry interface.

## Results

During polishing it was observed that the carbon-doped samples were hydrophobic in nature when compared to the hydrophilic nature of SiO<sub>2</sub> U and SiOF.<sup>38</sup> The hydrophobic nature of the carbondoped oxides was observed to be in the following descending order: SiOC SO > SiOC NSP > SiOC SP. To investigate the hydrophilic or hydrophobic nature of these films a detailed study of their chemical nature is required. Pressure and velocity do not have the expected influence on these samples. SiOC SO behaves like polymer materials, so the chemical interaction between the slurry and the film may be different than that of the other oxides.<sup>39</sup> From the nanoindentation results (Table II) it is seen that the hardness of SiOC SP is greater than that of SiOC NSP and SiOC SO. This indicates that Preston's equation may have to be revised so that properties of wafer materials, such as hardness of the wafer, may be included into the model. It was observed that the removal rate of softer films like SiOC SO was less than that of SiOC SP, which was comparatively harder. From the point of view of mechanical polishing in CMP, the material removal for softer films should be greater. This observation may indicate that when we consider the chemical polishing occurring in CMP, it may violate the mechanical polishing behavior, suggesting that material removal by the slurry on reaction with the wafer surface is not only dependent on the hardness of the films but also its reactivity with the surface of the films.

*Model validation and verification.*—Several points about the *MRR* (Eq. 4) deserve further mention before the model can be verified. The pressure influences the material removal rate through both the active abrasive number and the volume removed by a single abrasive. Thus, there is an increase in removal rate with an increase in pressure. As discussed by Luo and Dornfeld,<sup>22</sup> it was observed that the hardness of the pad influences the *MRR*. A softer pad yields



Figure 3. (a) Verification of the experimental removal rate with that calculated from the model for  $SiO_2 U$  at 1 psi, (b) model verification for  $SiO_2 U$  at 3 psi, (c) model verification for  $SiO_2 U$  at 6 psi, (d) model verification for  $SiO_2 U$  at 0.2 m/s, (e) model verification for  $SiO_2 U$  at 0.8 m/s, and (f) model verification for  $SiO_2 U$  at 1.2 m/s.



Figure 4. (a) Verification of the experimental removal rate with that calculated from the model for SiOF at 3 psi and (b) model verification for SiOF at 0.8 m/s.

a larger *MRR*.<sup>30</sup> The roughness parameters  $D_{sum}$ , *a*,*l*, and *R* of the pad have a large influence on *MRR*. *MRR* increases with an increase in pad roughness parameters. With these points in view the prediction of *MRRs* using Eq. 4 and 5 is verified. Though the form of the equation is complicated most of the properties of the consumables used in the experimentation have been measured. In spite of having most data, large error existed at certain process conditions and for certain wafer samples. Due to this, validity of the model can be estimated by comparing the order of the *MRR* prediction with the experimental results. Most of the models reported in literature are developed based on real-time CMP machines. Unlike the other models, this model was used to test the efficiency of a bench-top CMP tester as discussed earlier. Luo and Dornfeld validated their model by using experimental *MRR* results to calculate the unknown terms

3 psi (SiOC SP)

in the model and termed them as constants. For all further validations these calculated constants have been used. In this paper we have tried to validate the model by actually measuring most of the consumable properties and process parameters.

*Estimation of material removal rate.*—The mass of the material removed is estimated at first for  $SiO_2$  U wafers using the model described in Eq. 4. Preston's equation is not useful for estimating the order of the material removal due to the existence of the all-purpose parameter  $K_p$ . Therefore, the model predictions can be verified by the results obtained from polishing wafers at the conditions as listed in Table I. For the purpose of the experiments square samples having an area ( $A_0$ ) of approximately 1 in.  $\times$  1 in. were used. The dilution ratio  $d_s$  is 1, as undiluted oxide slurry was used for polishing.



Figure 5. Verification of the experimental removal rate with that calculated from the model for (a) SiOC SP at 3 psi and (b) model verification for SiOC SP at 0.8 m/s.



Figure 6. Verification of the experimental removal rate with that calculated from the model for (a) SiOC NSP at 3 psi and (b) model verification for SiOC NSP at 0.8 m/s.

ing. Most of the parameters (like  $D_{sum}a$ ,  $x_{avg}$ , b,  $\sigma$ ) needed to calculate the removal rates were measured directly and a few pad properties, which were difficult to measure directly, were estimated as described later.

As only the shore hardness of the pad used was available, the hardness of the viscoelastic pad was estimated based on the pad hardness values given in Ref. 22. IC1000/SuBa IV has a shore hardness of D 57. Based on the values published earlier,<sup>12</sup> the pad hardness was estimated to be  $15 \times 10^6$  Pa. The accuracy of the model could further be verified if the actual hardness values of the pad can be determined in SI units. The hardness of the wafers was measured using the nanoindentation technique.<sup>37</sup> Klebosol 1501 (oxide slurry) was used as the polishing slurry. The mean size of the silica abrasives was measured to be 66.24 nm with a standard deviation of 31.8 nm. The distribution of the abrasive size was found to be normal (measured by a laser scattering particle size distribution analyzer). The standard deviation of the abrasive size has a large influence on the MRR. The ratio b of contact area is difficult to measure directly. Hence, Eq. 6 was used. By substituting the down pressure applied, the hardness of the wafer, the size of the active abrasive (which is  $x_{avg} + 3\sigma$ ), and the roughness of the wafer in Eq. 6 the contact area ratio can be calculated. The values thus calculated would be different for all samples with varying hardness and pressure conditions under which they were polished. The values of b with varying hardness and pressure are listed in Table IV. The height of the asperities of the polishing pads is taken to be 100  $\mu$ m.<sup>40</sup> The radius of the asperity is about 100  $\mu$ m.<sup>40</sup> Because finding the density of the asperities  $(D_{sum})$  is difficult, the method used to estimate the number of abrasives trapped between the pad asperities and the wafer surface is described as follows:

It is seen that the number of abrasives trapped between the pad asperities and the wafer surface, derived in Ref. 22, is given by the equation

$$n = \frac{d_{\rm s}\rho_{\rm s}m_{\rm s-a}A_{\rm a}D_{\rm sum}al}{\rho_{\rm a}\frac{\Pi}{6}x_{\rm avg}^3}$$
[7]

In this equation  $d_s$  is dilution ratio of the slurry, which is assumed to be 1 as a nondiluted slurry is used in this work. *n*, the number of abrasives, can be calculated based on our assumption that there is an increase in the number of active abrasives with an increase in pres-

sure over the wafer-pad interface (Fig. 2). With a known asperity height (*l*) and area of wafer surface ( $A_a$ ), the volume of the slurry trapped ( $Vol_{trapped-slurry}$ ) between the wafer and the pad can be calculated. Once the volume of trapped slurry is known, the mass of the slurry ( $Mass_{trapped-slurry}$ ) can be calculated, as the density ( $\rho_s$ ) of the slurry is known. Because the abrasive concentration of the slurry ( $m_{s-a}$ ) is also known, the mass of the abrasives ( $Mass_{trapped-abrasives}$ ) in the trapped slurry can be calculated. Now the mass of abrasives trapped can be used to calculate the volume of trapped abrasives ( $Vol_{trapped-abrasives}$ ), as density of abrasives ( $\rho_a$ ) is known. Knowing the volume of *n* number of trapped abrasives, the volume occupied by a single abrasive ( $Vol_{single-abrasive}$ ) can be estimated. This method used to estimate *n* is formulated as follows

$$Vol_{trapped-slurry} = l \times A_a$$
 [8]

$$Mass_{\text{trapped-slurry}} = Vol_{\text{trapped-slurry}} \times \rho_s$$
[9]

$$Mass_{trapped-abrasives} = Mass_{trapped-slurry} \times m_{g-a}$$
 [10]

$$Vol_{\text{single-abrasive}} = \frac{4}{3} \Pi \left(\frac{x_{\text{avg}}}{2}\right)^3$$
 [11]

$$Vol_{trapped-abrasives} = \frac{Mass_{trapped-abrasives}}{\rho_a}$$
[12]

$$n = \frac{Vol_{\text{trapped-abrasives}}}{Vol_{\text{single-abrasive}}}$$
[13]

The number of trapped abrasives *n*, calculated using the previous method for all the samples, is shown in Table V. Because we made an assumption of an increase in the contact area at the wafer-pad interface with an increase in pressure, *n* also would increase with an increase in pressure (Fig. 2). The mean area of the total asperities was given to be around  $0.005A_a$  under no-load condition.<sup>13</sup> We assumed the mean asperity area to be  $0.006A_a$ ,  $0.012A_a$ , and  $0.018A_a$  at 1, 3, and 6 psi, respectively. These constants were chosen assum-



Figure 7. (a) Verification of the experimental removal rate with that calculated from the model for (a) SiOC SO at 1 psi, (b) model verification for SiOC SO at 3 psi, (c) model verification for SiOC SO at 6 psi, (d) model verification for SiOC SO at 0.2 m/s, (e) model verification for SiOC SO at 0.8 m/s, and (f) model verification for SiOC SO at 1.2 m/s.

ing an increase of 0.001 for a pressure of 1 psi. Later, for an increase in 2 psi from pressure 1-3 psi, the asperity area was calculated to be twice the mean asperity area for 1 psi. Similarly, for an increase in 3

psi from pressure 3-6 psi, the asperity area was calculated to be three times the mean asperity area for 1 psi. Equation 4 can also be written as  
 Table V. Ranges for parameters used in the model for calculating the MRR.

k	2.44		
$\rho_w (gm/mm^3)$	$2.33 \times 10^{-3}$		
$A_{\rm a}$ (in. <sup>2</sup> )	1 (approx)		
$d_{s}$	1		
$m_{s-a}$ (%)	0.288		
<i>l</i> mm	$100 \times 10^{-3}$		
$\rho_a (g/mm^3)$	$2.19 \times 10^{-3}$		
$\rho_s (g/mm^3)$	$0.9971 \times 10^{-3}$		
π	3.1415		
$x_{avg} (mm)$	$66.24 \times 10^{-6}$		
σ (mm)	$31.8 \times 10^{-6}$		
$H_{\rm p}$ (Pa)	$15 \times 10^{6}$		
$P_0'$ (Pa)	6894.76	20,684	41,368.5
V (mm/h)	720,000	2,880,000	4,320,000

$$MRR_{\text{mass}} = n \frac{3\sqrt{2}}{12} k^2 \rho_{\text{w}} x_{\text{avg}}^2 \frac{1}{(bH_{\text{w}})^{3/2}} \left[ 1 - \Phi \left( 3 - \frac{0.25(x_{\text{avg}} + 3\sigma) \left( \frac{1}{H_{\text{p}}} + \frac{2}{H_{\text{w}}} \right)}{\sigma} \frac{P_0}{b} \right] \right] P_0^{3/2} V$$
[14]

For all calculations of  $MRR_{\text{mass}}$  and related discussions in the coming sections, Eq. 14 has been used; subsequently,  $MRR_{\text{thickness}}$  is calculated using Eq. 5.

### Discussion

With different ranges of parameters as shown in Table I, the model as given in Eq. 14 and 5 was verified by comparing the model *MRR* values with the experimental values at different conditions of down pressure and platen speed. The pad and slurry properties remain the same for each pressure condition. Pad properties like  $(D_{sum} \times a)$  change with the amount of pressure applied (Table IV). Figure 3-7 show the difference between the material removal rates calculated experimentally and by using the model. The experiments were performed at three different pressures and velocities. From Fig. 3a-c it is seen that the model and experimental values agree at lower velocity conditions or platen speeds. At higher velocities the error between the model and experimental values tends to increase. The possible reasons for the existence of this error are described as follows.

The type of the contact mode at the wafer-pad interface may contribute to the error. Although the model is developed for a solidsolid contact mode, at very high velocities the mode of contact may be more like hydrodynamic in nature, because of which the removal rate might not increase with the *MRR* given by the model at higher velocity conditions. Another reason behind the error in measurement of the material removal is the absence of upper rotation in the bench-top CMP machine. However, it is believed that the error contribution due to this is minimal, as most of the times it is the edges that get polished even in the case of real-time CMP. It was seen that if the *MRR* calculation was restricted to the points on the anterior side (the side facing the operator) in case of clockwise rotation of the platen, the probability of error is reduced to a great extent. As is the case with real-time CMP, maximum material removal occurs at the anterior edge.

From Fig. 4a and b it can be seen that in the case of SiOF the model gives quite accurate predictions. The thickness of SiOF was much smaller compared to the other doped samples. Within a specific time most of the SiOF film was polished and thickness mea-

surement after polish was much easier and accurate compared to the SiOC samples. This also proves that the absence of upper rotation is not very significant.

For SiOC SP (Fig. 5a and b), the model and experimental values were very different. For similar process conditions the MRR predicted by the model was much lower than the experimental MRR. As seen from Fig. 6a and b, the error was less when compared with SiOC SP. The error in the experimental and model values for MRR at different psi and velocity conditions was almost constant. The model and the experimental values are closer in this case, when compared with SiOC SP. The error was found to be significantly large at 6 psi pressure and 0.8 m/s velocity. Figure 7a-f for SiOC SO shows that experimental values were higher than the model values. It is also seen that at 1.2 m/s the experimental and model values match at a pressure between 1 and 3 psi and also between 3 and 6 psi. In comparison to the MRR values obtained for SiO<sub>2</sub> U, the MRR value for SiOC SO was much less, even though the later material has a lower hardness. The reasons for the undesired results can be attributed to the influence of parameters like  $H_w$  and  $R_a$  on the model. As stated before we could see that the hardness of the wafers did not influence the calculation of MRR to a large extent, while the right method of incorporation of the hardness factor would have influenced the calculations to a large extent. Another factor  $R_{a}$  was considered to be the same for all materials, while it may possess different values based on the polished surface. From the equation it is seen that the removal rate model is largely and directly dependent on this factor. Accurate measurement of roughness values through techniques like atomic force microscopy (AFM) may produce better results. Research in this direction is underway. In addition, other factors like the passivation rate are also not considered.<sup>41</sup> Inclusion of variables, which can quantify the reactions occurring at the waferslurry interface, could add valuable insight.

The Preston equation was verified for both the experimental MRR values and the model MRR values. Figure 8a-e shows the variation of MRR with pressure  $\times$  velocity (psi  $\times$  m/s). The regression coefficient is also calculated for the linear line fitted for the values plotted on the graph. It is seen than the  $R^2$  value for the model is very close to 1, indicating good fit and linearity, while in the case of experimental values it is seen that  $R^2$  values are as low as 0.619 (for SiOC SO). It was seen that the model (Eq. 14) follows Preston's equation for all samples for a given set of conditions, while the experimental values did not follow the Preston equation in Fig. 8e. Figure 8 shows that though the model follows Preston's equation for all oxide samples, it does not follow the same pattern as the experimental values for SiOC NSP (Fig. 8d) and SiOC SO (Fig. 8e). The data are scattered for the experimental values in Fig. 8d and e, but that is not the case with the model values. This may indicate that slurries suitable to polish SiOC might give better removal rate predictions. Inclusion of parameters like slurry reactivity may improve the model (Eq. 14) used for calculating the material removal rate. This would also help in understanding the CMP process at the nanoscale level.

## Conclusions

A bench-top CMP polisher was used to study the polishing behavior of doped and undoped oxide low-*k* films. Klebosol 1501 was found to be good for polishing SiO<sub>2</sub> U and SiOF films as it displays ideal behavior. Mechanical polishing is the same for all samples; therefore, the nonlinearity observed in the Preston equation for all SiOC samples is due to the difference in the chemical composition, structure, and reactivity of the surface with the slurry. This phenomenon may occur because the slurry does not react with the surface of SiOC films as aggressively as with SiO<sub>2</sub> U films, thereby making mechanical action on SiOC films more difficult. Using slurries designed for polishing SiOC would have produced a higher polishing rate.

Experimental results are well correlated with the predicted values of the model. This model can be used for process control and optimization. The validated model not only integrates the process pa-



rameters pressure and velocity as compared with previous approaches to modeling, but also other important parameters including abrasive size, wafer hardness, pad hardness, and roughness into the same formulation to predict the MRR. The model is very sensitive to slurry properties and pad roughness parameters. Very precise control of slurry and pad properties is possible using this model because of its sensitivity to a wide range of parameters.

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This comprehensive model proves that the bench-top tester can be used as a real-time R&D tool. The multisensing technology allows for monitoring polishing processes on wafers with any layers, including sensitive measurements of material removal and other polishing characteristics. These novel *in situ* measurements ensure effective process development. The dramatically reduced time of process development allows for much faster time-to-market. The accuracy and repeatability of the measurements allows for effective qualification, incoming inspection, and ongoing functionality testing of polishing pads, slurries, conditioners, retaining rings, etc. The capability of accommodating small wafers and pads with small amounts of slurry make the cost of testing much smaller than that on a full-scale production CMP machine. The cost of polishing per wafer may be 10-15 times more in real-time polishing.

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